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Geochronology of the Mons Cupri Archaean Volcanic Centre, Pilbara block, Western Australia

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Abstract

The results of Rb-Sr geochronology on four suites of felsic rocks from the vicinity of the Archaean Mons Cupri volcanic centre in the Pilbara Block of Western Australia are presented. The Caines Well Granite, which represents the foliated granitoid basement to the volcanic complex has a metamorphic age of 2 713 ± 53 Ma and an intial ratio of 0.7040 ± 0.0006 on a closely fitted isochron. A primary age of approximately 3 000 Ma can be calculated using a single stage strontium evolution analysis for this granite. This age is in good agreement with other published data. The Mons Cupri Granite is a massive intrusive body and has an age of 2 366 ± 60 Ma, which is significantly younger than similar granitoids in the East Pilbara. The Mons Cupri Porphyry gives an age of 2 610 ± 80 Ma whereas the Mount Brown Rhyolite has an age of 2 331 ± 42 Ma. These Rb-Sr ages represent updated events rather than the primary ages of the rock units.

Introduction

The Pilbara Block occupies approximately 60 000 km^2 of the northern part of Western Australia, and is an Archaean granite-greenstone terrain where domal granitic batholiths up to 100 km across are separated by greenstone belts made up of metamorphosed volcanic and sedimentary sequences.

The Archaean greenstone succession comprises folded volcanic and sedimentary units that can be traced across the Pilbara region (Hickman 1983). Two major groups within the layered greenstone succession have been defined—the Warrawoona and Gorge Creek Groups. The Warrawoona Group consists of sequences of tholeiitic and komatiitic lavas and intrusions interlayered with cherty sediments and sequences of calc-alkaline volcanics cut by subvolcanic intrusives; the group is overlain unconformably by the dominantly sedimentary rocks of the Gorge Creek Group (Table 1). These units, together with the Whim Creek Group and the Louden and Negri Volcanics which uncomformably overlie the Gorge Creek Group in the West Pilbara, are called the Pilbara Supergroup by Hickman (1981). The Pilbara Supergroup is in turn overlain by the Fortescue Group which is believed to have been deposited between 2 700 and 2 800 m.a. ago (Trendall 1983).

This paper presents Rb-Sr geochronological results from the mineralised Mons Cupri volcanic centre, which is situated some 100 km south-west of Port Hedland, in the western part of the Pilbara Block.

Geology of the Mons Cupri Area

The Whim Creek Group contains a partly subaerial sequence of calc-alkaline volcanics with associated epiclastic sediments which include shallow and deeper-water facies. Volcanogenic Fe-Cu-Zn sulphide mineralisation occurs within the Whim Creek Group at Whim Creek and Mons Cupri (Marston & Groves 1981).

Fitton *et al.* (1975) defined the Whim Creek Group as a volcanic and sedimentary succession composed of four formations—The Warambie Basalt, Mons Cupri Volcanics, Constantine Sandstone and the Mallina Formation. Hickman (1983) has redefined the Whim Creek Group as consisting, in ascending order, of the Warambie Basalt, Mons Cupri Volcanics and the Rushall Slate, and considers the Constantine Sandstone and the Mallina Formation to be part of the Gorge Creek Group (Table 1). Barley *et al.* (1984) point out that there is some uncertainty as to whether the Whim Creek Group completely post-dates the Gorge Creek Group or contains lateral equivalents of units contained in the Gorge Creek Group. The Whim Creek Group, as defined by Hickman (1983), is confined to the Whim Creek Belt which lies to the south of the Caines Well Granite between the Balla Balla—Mount Negri area and Warambie Homestead.

The Warambie Basalt is a vesicular and amygdaloidal basalt which is the basal formation of the Whim Creek Group. It ranges in composition from basalt to andesite (Hickman 1983).

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Table 1

Stratigraphy of the Upper Pilbara Supergroup (After Hickman 1983)

	Group	Maximum unit	Thickness(m)	Lithology
	Fortescue Group	Mount Roe Basalt	200	Massive to porphyritic columnar and amaygdaloidal basalt
PILBARA SUPERGROUP		Negri Volcanics	200	Basalt and andesite
		Louden Volcanics	1 000	Basalt and ultramafics
	Whim Creek Group	Rushall Slate	200	Slate and phyllite
		Mons Cupri Volcanics	700	Felsic Volcanics
		Warambie Basalt	200	Vesicular basalt
	Gorge Creek Group	Various formations	12 500	Sedimentary rocks
	Warrawoona Group	Various formations	15 600	Tholeitic and komatiitic lavas and intrusions

The Mons Cupri Volcanics crop out in an arcuate belt up to 5 km wide which follows the southern and eastern margins of the Caines Well Granite. The base of the Mons Cupri Volcanics is predominantly dacitic. The lava is fine-grained and contains amygdales filled with quartz, chlorite and carbonate minerals. The sequence is intruded by feldsparphyric dacite plugs. The basal unit is overlain by the Mount Brown Rhyolite Member which is a cream, massive rock, commonly spherulitic and containing fragments of aphanitic felsic lava. The Mount Brown Rhyolite is overlain by a sequence of felsic agglomerate containing thin intercalations of felsic lava and tuff. The agglomerate is the host rock to the Mons Cupri copper deposit. Above the agglomerate finer pyroclastic rocks, tuffaceous sandstone and minor conglomerate marks the top of the Mons Cupri Volcanics (Hickman 1983).

The Rushall Slate is defined by Hickman (1983), and consists of grey slate and phyllite, subordinate flows of andesite and dacite, quartzite, and lenses of felsic tuff.

The geology of the Mons Cupri volcanic centre has been documented by Miller & Gair (1975) and Sylvester (1976). Figure 1 shows the volcanic centre geology as interpreted by Sylvester (1976). The oldest rocks in the area are granitoids of the Caines Well Granite, one of the large granitoid domes which are of granodiorite composition and are commonly strongly foliated. For this study, samples were collected from exposures in the Sherlock River, 25 km west of Mons Cupri.

Resting unconformably upon these granitoids in the vicinity of Mons Cupri, is a sequence of intermediate to felsic metavolcanics, the Mons Cupri Volcanics. The lower units are largely tuffaceous, although amygdaloidal flows have been recorded and are mostly of rhyodacite to rhyolite composition, although some dacites and andesites are present. This sequence has been intruded by feldspar porphyries of rhyolite composition. These have broken surface to produce agglomerates, and the Mons Cupri base metal deposit is associated with one such agglomeratic unit.

The agglomerates are overlain by felsic tuffs, rhyolitic and andesitic flows, thin chert horizons and intercalated slates of the Rushall Slate. This sequence is overlain unconformably by andesitic flows and tuffs of the Negri Volcanics. Intruding all of these rocks is a large plug of spherulitic rhyolite, the Mount Brown Rhyolite, which has produced the domal structure present in the area. Mafic intrusive rocks of the Millindina Complex range in composition from peridotite to granophyre, and are widespread throughout the area, postdating the Mount Brown Rhyolite. The youngest Archaean rocks in the area are subvolcanic adamellite intrusives which have been called the Mons Cupri Granite by Sylvester (1976).

A review of radiometric ages obtained for rock units within the Pilbara Block has been given by De Laeter *et al.* (1981a), and more recently by Blake & McNaughton (1984). Compston & Arriens (1968) reported an age of approximately 2 940 Ma for acid lavas from Whim Creek, although Arriens (1975) stated that this age may need to be revised. However Fitton *et al.* (1975), quoting a personal communication from Arriens, suggested that the age may be between 2 300 and 2 500 Ma.

Two galena samples from the stratiform Salt Creek deposit, within felsic volcanics of the Whim Creek Group, give a model age of 2 950 ± 10 Ma (Richards & Blockley, 1984). The authors argued that the base of the Fortescue Group cannot be younger than 2 800 Ma. Gulson *et al.* (1983) also obtained a Pb-Pb isochron age of 2 940 ± 20 Ma for felsic volcanics at Salt Creek. Richards (1983) also reports an age of 2 930 ± 10 Ma for a galena from Mons Cupri. Fletcher (Pers. comm.) reports a Sm-Nd model age of 3 000 ± 40 Ma from the Mount Brown Rhyolite.

Korsch & Gulson (1986) have recently dated some samples from the Millindinna Complex to give a Sm-Nd whole rock/mineral age of 2 830 ± 20 Ma and a Pb-Pb whole rock age of 2 960 ± 20 Ma, the Millindinna Complex comprises a suite of layered rocks ranging in composition from mafic to ultramafic around the margin of the Caines Well Granite (Fitton *et al.* 1975). The authors

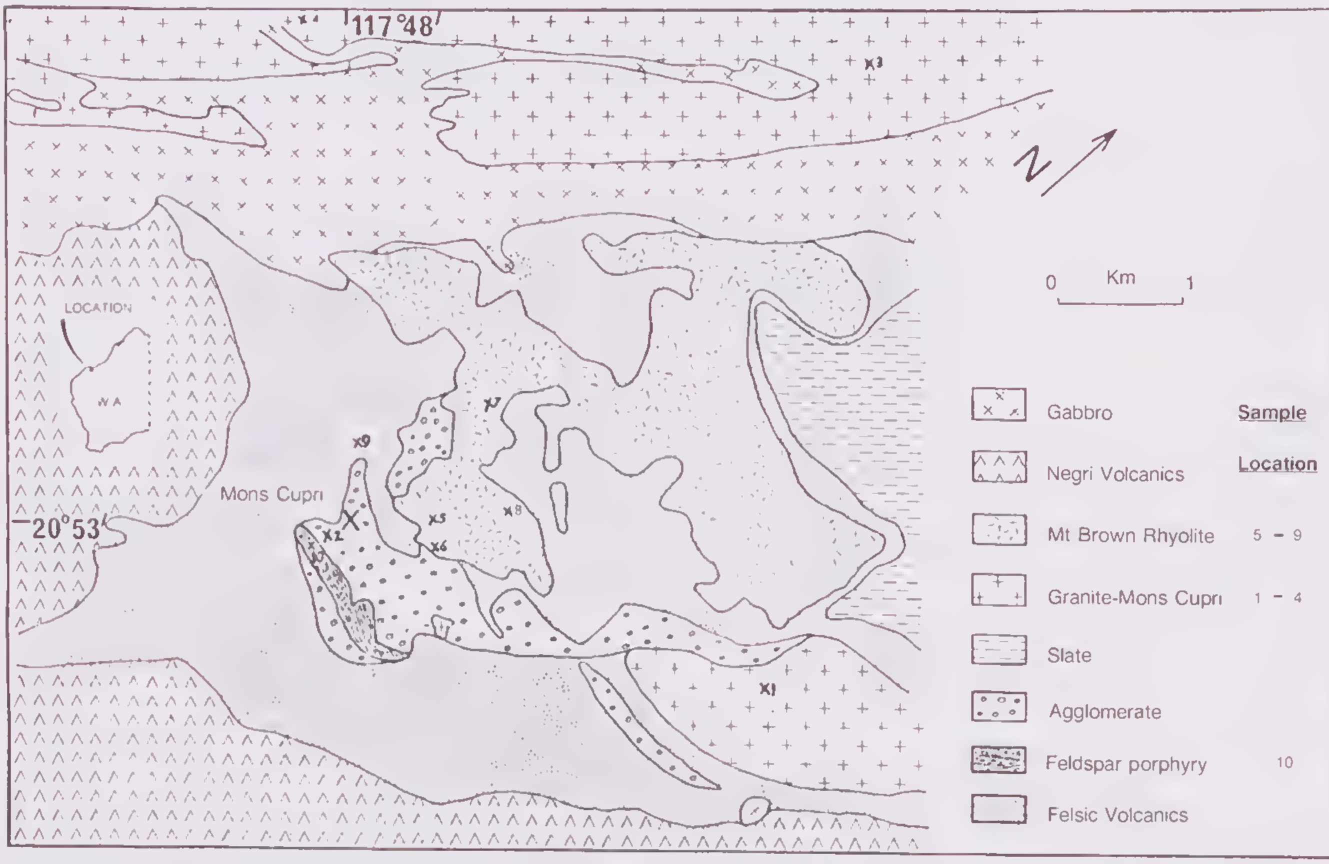

Figure 1—Geology of the Mons Cupri Volcanic Centre showing the sample locations for the Mons Cupri Granite, the Mount Brown Rhyolite and the Mons Cupri Porphyry. Samples from the Caine's Well Granite were collected from the vicinity of the Sherlock River, some 25 km west of Mons Cupri.

point out that the different ages obtained by the two methods probably arises from the limited disperson in lead isotope ratios in the samples, but believe that an age of 2 900 Ma is consistent with the geology and geochronology of the area. Korsch & Gulson (1986) argue that the time difference between the formation of the Whim Creek Group and the emplacement of the Millindinna Complex is probably quite short.

The base of the Warrawoona Group is well established at approximately 3 500 Ma, but the duration of volcanism and the onset of the Gorge Creek sedimentation is still an open question (Blake & McNaughton 1984). However geochronological evidence from zircons from the Boobina Porphyry (Pidgeon 1984) and galena Pb model ages from veins in the upper part of the Warrawoona Group (Richards *et al.* 1981), suggests an end of volcanism at about 3 300 Ma. Thus the Gorge Creek and Whim Creek Groups are constrained between 3 300 Ma and 2 800 Ma.

Analytical Methods

Whole rock major element analyses were carried out by X-ray fluorescence spectrometry using the method of Norrish & Chappel (1967), except for sodium which was determined by atomic absorption spectroscopy.

The experimental procedures for the Rb-Sr analyses are essentially as reported by De Laeter *et al.* (1981b). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 strontium standard measured during this project was 0.71021 ± .00012, normalized to a $^{88}Sr/^{86}Sr$ value of 8.3752. Regression analyses of the data was carried out using the least squares program of McIntyre *et al.* (1966), with a ^{87}Rb decay constant of 1.42×10^{-11}yr. Measured Rb and Sr concentrations and Rb/Sr ratios as determined by X-ray fluorescence spectrometry are listed with the mass spectrometric determinations in Table 2. Errors accompanying the data are at the 95% confidence level although the Rb and Sr concentrations are only accurate to ± 5%.

Results and Discussion

Major element whole rock analyses of some of the samples used for geochronology are listed in Table 3. The results demonstrate that these rocks are relatively unaltered and of comparable composition to typical calc-alkaline rocks of similar silica content.

The nine samples of Caines Well Granite define a well-fitted isochron as shown in Figure 2. The age of these samples is 2713 ± 53 Ma and the initial $^{87}Sr/^{86}Sr$ ratio is 0.7040 ± 0.0006 with a mean square of weighted deviates (MSWD) of 0.51. Two of the samples are mineral separates extracted from the corresponding whole rock samples. Blake & McNaughton (1984) have shown that granitoids and gneisses from batholiths of the Pilbara Block show a range of ages of approximately 3 500 to 2 850 Ma by U-Pb, Pb-Pb and Sm-Nd geochronology, whereas the corresponding Rb-Sr ages tend to be lower. Oversby (1976) detected metamorphic overprinting in similar rocks at 2 751 ± 31 Ma, 2 786 ± 38 Ma and 2 769 ± 13 Ma.

Table 2

Rb-Sr Analytical Data for Mons Cupri Volcanic Centre Samples

Sample	Rb(ppm)	Sr(ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Description
Caines Well Granite						
90223	61	502	0.123 ± 0.002	0.358 ± 0.005	0.71799 ± 0.00019	Recrystallised biotite granodiorite
83995(L)	120	654	0.183 ± 0.002	0.529 ± 0.007	0.72457 ± 0.00031	'Light' mineral separate
83995	75	405	0.188 ± 0.002	0.544 ± 0.007	0.72513 ± 0.00029	Recrystallised biotite granodiorite
90224	115	510	0.228 ± 0.003	0.660 ± 0.008	0.72997 ± 0.00034	Recrystallised biotite granodiorite
90225	61	256	0.236 ± 0.003	0.68 ± 0.01	0.73076 ± 0.00033	Recrystallised biotite granodiorite
90226	71	299	0.240 ± 0.003	0.70 ± 0.01	0.73164 ± 0.00022	Recrystallised biotite hornblende granodiorite
84065	115	380	0.300 ± 0.004	0.87 ± 0.01	0.73864 ± 0.00025	Recrystallised biotite granodiorite
84066(L)	204	421	0.484 ± 0.005	1.40 ± 0.02	0.75862 ± 0.00024	'Light' mineral separate
84066	170	265	0.640 ± 0.007	1.86 ± 0.02	0.77703 ± 0.00025	Recrystallised biotite granodiorite
Mons Cupri Granite						
84000	130	180	0.72 ± 0.007	2.08 ± 0.02	0.78114 ± 0.00031	Recrystallised sericitic, chloritic adamellite
83996	160	110	1.45 ± 0.02	4.19 ± 0.04	0.85435 ± 0.00033	Sericitsed and carbonated adamellite
83998	70	37	1.89 ± 0.02	5.64 ± 0.05	0.91394 ± 0.00029	Recrystallised chloritic adamallite
84003	133	49	2.69 ± 0.03	7.97 ± 0.08	0.98399 ± 0.00025	Recrystallised chloritic adamallite
83999	75	22	3.41 ± 0.03	10.0 ± 0.1	1.06753 ± 0.00033	Recrystallised chloritic adamallite
* 84002	334	30	10.9 ± 0.1	34.3 ± 0.3	1.63373 ± 0.00035	Sericitised, silicified and chloritised adamellite
84001	277	23	11.9 ± 0.1	38.7 ± 0.4	2.03424 ± 0.00040	Sericitised, chloritised and carbonated adamellite-granite
Mt. Brown Thyolite						
84004	30	165	0.178 ± 0.002	0.52 ± 0.05	0.73118 ± 0.00015	Chloritic, fine-graned rhyolite
83987(L)	265	178	0.68 ± 0.007	1.98 ± 0.02	0.77990 ± 0.00014	'Light' mineral separate
83987	85	120	0.71 ± 0.007	2.03 ± 0.02	0.78209 ± 0.00018	Massive spherulitic rhyolite
83992	80	90	0.89 ± 0.009	2.53 ± 0.03	0.79711 ± 0.00025	Slightly sericitised rhyolite
83993	110	115	0.95 ± 0.01	2.77 ± 0.03	0.80698 ± 0.00023	Massive, fine-grained rhyolite
83988	125	130	0.98 ± 0.01	2.86 ± 0.03	0.81146 ± 0.00022	Massive spherulitic rhyolite
83989	135	40	3.38 ± 0.03	9.65 ± 0.1	1.03813 ± 0.00031	Sericitised and carbonated spherulitic rhyolite
Mons Cupri Porphyry						
84010	60	160	0.38 ± 0.004	1.07 ± 0.01	0.74171 ± 0.00025	Brecciated, chloritised and carbonated feldspar porphyry
84017	84	109	0.79 ± 0.008	2.30 ± 0.02	0.79126 ± 0.00018	Silicified feldspar porphyry
84013	130	155	0.90 ± 0.009	2.62 ± 0.03	0.80184 ± 0.00029	Brecciated, sericitised feldspar porphyry
84012	80	45	1.78 ± 0.02	5.24 ± 0.05	0.89758 ± 0.00031	Brecciated, sericitised chloritised feldspar porphyry
84015	208	73	2.87 ± 0.03	8.5 ± 0.09	1.02034 ± 0.00032	Slightly chloritic feldspar porphyry
84014	171	47	3.65 ± 0.04	11.0 ± 0.01	1.12206 ± 0.00035	Sericitised feldspar porphyry

* This sample is not included in the isochron for the Mons Cupri Granite.

Table 3

Representative analyses of calc-alkaline volcanics and associated high level intrusives from the Mons Cupri Volcanic Centre

	Caines Well Granite			Mons Cupri Granite				Mount Brown Rhyolite					Mons Cupri Porphyry		
	83995	84065	84066	84000	83996	82998	83999	83987	83992	83993	83988	83989	84010	84013	84012
SiO_2	73.55	73.37	70.13	72.15	65.57	76.20	76.87	73.88	77.05	75.41	76.39	76.19	70.54	77.39	67.45
TiO_2	0.16	0.16	0.17	0.25	0.33	0.32	0.32	0.50	0.45	0.48	0.45	0.45	0.56	0.56	0.68
Al_2O_3	14.66	16.05	16.30	14.13	15.07	11.15	10.99	12.87	12.41	12.67	12.61	11.50	12.67	12.33	13.59
Fe_2O_3	0.30	1.00	2.39	0.76	0.62	1.42	1.13	0.38	0.30	0.43	0.04	0.71	0.35	0.49	0.71
FeO	0.91	0.01	0.01	1.42	3.03	1.66	1.86	1.40	0.71	0.33	0.75	1.56	3.68	0.53	5.93
MnO	0.02	0.03	0.03	0.03	0.06	0.05	0.05	0.05	0.03	0.03	0.04	0.04	0.08	0.04	0.10
MgO	0.41	0.18	0.62	0.63	2.95	0.19	0.18	0.26	0.17	0.16	0.15	0.89	0.80	0.71	1.40
CaO	1.97	1.40	2.17	1.35	1.52	0.70	0.66	1.29	0.31	0.91	1.26	1.34	1.25	0.48	1.07
Na_2O	4.75	4.45	4.72	3.90	0.57	3.66	3.39	5.33	4.78	4.74	3.57	0.18	4.14	3.22	1.96
K_2O	2.76	3.94	2.91	4.37	5.36	3.91	4.13	2.95	3.05	3.94	3.62	4.35	3.52	2.52	3.19
P_2O_5	0.05	0.04	0.03	0.09	0.13	0.03	0.03	0.13	0.12	0.13	0.11	0.12	0.12	0.05	0.14
LOI	0.90	0.77	0.74	1.66	4.72	0.67	0.67	1.71	1.03	1.40	1.06	0.34	2.53	2.07	3.62
Total	100.44	101.40	100.22	100.74	99.93	99.96	100.28	100.75	100.41	100.63	100.05	97.67	100.24	100.39	99.84

Strontium evolution analysis of the data from Caines Well Granite suggests a mantle evolution age of approximately 2 975 Ma assuming single stage evolution. This value has been calculated from the measured age of 2 713 Ma and the initial ratio of 0.7040, assuming a $^{87}Rb/^{86}Sr$ ratio which is the arithmetic mean of the suite of samples. Mantle Sr evolution was assumed to be linear from 0.6990 at 4 600 Ma to 0.7040 at present (Faure & Powell 1972). The primary Rb-Sr age of approximately 2 975 Ma is in good agreement with ages determined by more robust geochronological techniques on Pilbara Block Batholiths.

Six of the seven Mons Cupri Granite samples fall on an isochron shown in Figure 3. The model 1 age and initial ratio is 2 430 ± 25 Ma and 0.7089 ± 0.0017 respectively. However the MSWD of 26 indicates a poor fit, and a model 3 age and initial ratio of 2 366 ± 60 Ma and 0.7156 ± 0.011 respectively are to be preferred.

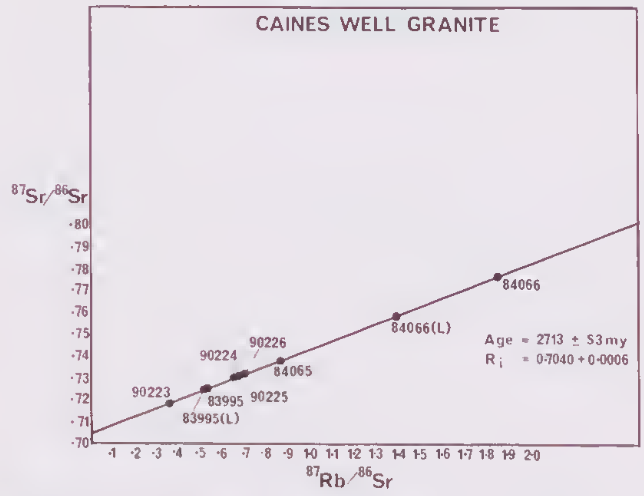

Figure 2—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ diagram for samples from Caine's Well Granite.

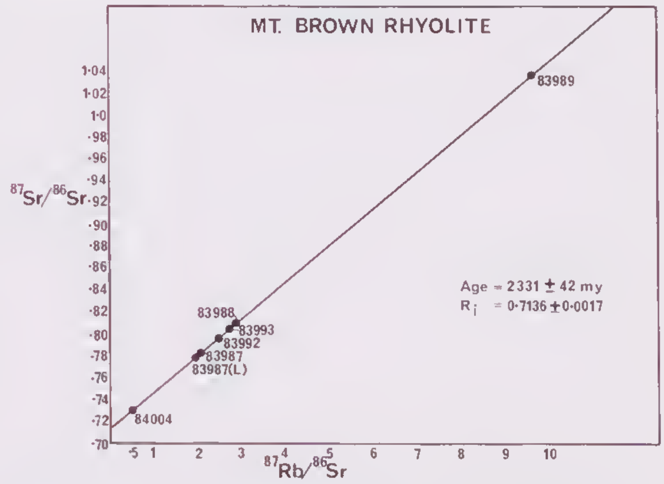

Figure 4—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ diagram for samples from Mount Brown Rhyolite.

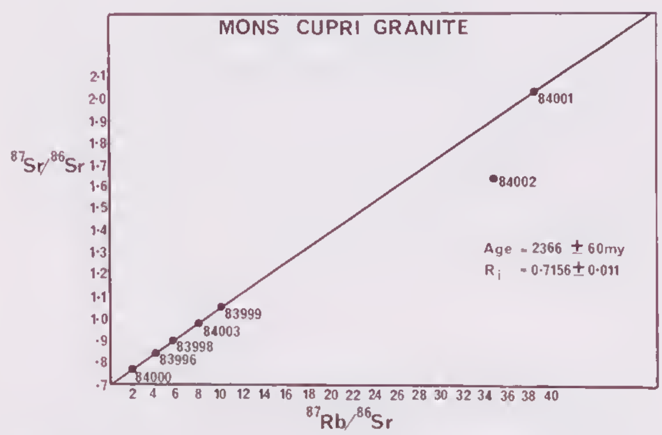

Figure 3—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ diagram for samples from Mons Cupri Granite.

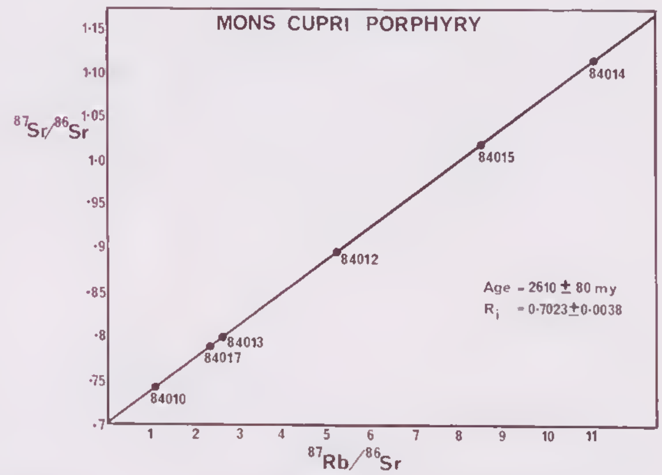

Figure 5—$^{87}Sr/^{86}Sr$ vs $^{87}Rb/^{86}Sr$ diagram for samples from Mons Cupri Porphyry.

The Mons Cupri Granite is one of the young massive intrusive bodies which are common throughout the Pilbara Block. It differs from the Caines Well Granite in being of adamellite composition and having higher Rb/Sr ratios. The age of 2 366 ± 60 Ma is somewhat younger than similar granitoids in the East Pilbara, where dates of 2 670 ± 95 Ma and 2 606 ± 128 Ma have been reported (De Laeter & Blockley 1972, De Laeter *et al.* 1975). The Moolyella and Cooglegong adamellites are intermediate level structural types, whereas the chemistry and petrography of the Mons Cupri Granite show it to be of a high level subvolcanic type.

The Mount Brown Rhyolite samples give a Model 1 age of 2 331 ± 27 Ma and an initial ratio of 0.7136 ± 0.0008 (Figure 4). The MSWD of 3.6 indicates a reasonably good fit of the seven samples, but a more accurate estimate of the age and initial ratio would be given by the Model 3 values of 2 331 ± 42 Ma and 0.7136 ± 0.0017 respectively. The data may reflect the local outpouring of the lowermost Fortescue Group volcanics (Mount Roe Basalt), as suggested by Oversby (1976), but more likely relates to the D4 or D5 deformations documented by Hickman (1983). The Rb-Sr age is significantly less than the Sm-Nd model age of 3 000 ± 40 Ma reported by Fletcher (Pers. comm.).

The feldspar porphyry samples fit an isochron (Figure 5), which gives a Model 1 age of 2 617 ± 28 Ma and initial ratio of 0.7020 ± 0.0011. However the samples give a MSWD of 9.1, and a more realistic estimate would be a Model 4 age and initial ratio of 2 610 ± 80 Ma and 0.7023 ± 0.0038 respectively. The Rb-Sr age of the porphyry from Mons Cupri is intermediate in value between the ages obtained for the Caines Well and Mount Brown Rhyolite. Although this is consistent with the geology of the region, it must be pointed out that since the Rb-Sr isochron ages are updated ages, the sequence of measured ages do not represent the ages of emplacement of the various rock units.

The calculated primary age of the Caines Well Granite of approximately 3 000 Ma is however, consistent with the other published age data for the Salt Creek deposit and the Millindinna Complex.

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Origin of limestone lenses in Perth Basin yellow sand, southwestern Australia

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Abstract

Aeolian limestone lenses are common in thick sections of yellow quartz sand in the Pleistocene sequences of the Perth Basin, southwestern Australia. Previous workers presumed that these lenses are undigested residuals as the coastal limestones purportedly decalcified to quartz sand. Evidence presented here suggests that the limestone lenses are outliers of calcareous dunes that migrated inland over yellow quartz sand from a Pleistocene coastal zone. Subsequently the lenses were buried by sea-ward influx of yellow quartz sand. This interpretation is based on size, geometry, lithology and stratigraphy of limestone lenses, and their stratigraphic relationships with encompassing yellow quartz sand, and comparisons with geometry, stratigraphy and lithology of Holocene dune deposits.

Introduction

Lenses of aeolian limestone are commonly encountered in thick sections of yellow quartz sand in Pleistocene sequences of the Perth Basin, southwestern Australia. Generally these limestone lenses, also termed "limestone floaters", have been interpreted as undigested residuals of limestone which have formed as the Pleistocene calcareous aeolianites of this region purportedly decalcified to form quartz sand sheets and dunes (McArthur & Bettenay 1960, 1974). Probably the first reference to this process of decalcification is that of Woodward (1890), but subsequent authors have reached similar conclusions or accepted the conclusions of earlier workers (Clark 1926, Crocker 1946, Prider 1948, Fairbridge 1950, 1953, 1954, Fairbridge & Teichert 1953, McArthur & Bettenay 1960, 1974, Welch 1964, Lowry 1967, 1977, Low 1971, Baxter 1972, Johnstone *et al.* 1973, Lissiman & Oxenford 1973, Mulcahy 1973, Mulcahy & Churchward 1973, Wilde & Low 1975, McArthur 1976, Playford *et al.* 1976, and Wyrwoll & King 1985).

This paper presents an important and radically different interpretation of the origin of limestone lenses. It is concluded that limestone lenses in Perth Basin yellow sand, are the buried outliers of attenuated parabolic calcareous dune that have migrated inland from a Pleistocene coastal zone. This interpretation is based on criteria of size, geometry, and stratigraphic relationships of limestone lenses to the surrounding quartz sand, and comparisons with geometry, stratigraphy and lithology of Holocene dunes. Such an interpretation depicts a very different conclusion to the model currently accepted and provides important implications for the stratigraphic relationship of limestone and yellow sand. However, it should be stressed that this paper concentrates on the origin of limestone lenses that occur in yellow sand sequences, and not on the origin of the yellow sand. The origin of the yellow sand as aeolian deposits is discussed later only in the light of the interpretation that limestone lenses are buried Pleistocene calcareous dunes and not undigested residuals.

The philosophy of approach in this paper has been to document the geometry and stratigraphy of Holocene parabolic dunes and their geomorphic variations and diagenesis. This forms the basic foundation work to understanding the origin of limestone lenses, and the information from the Holocene is applied to interpret the Pleistocene sections.

Methods

Stratigraphic information from Holocene quartzose carbonate sand, Pleistocene yellow quartz sand and Pleistocene quartzose limestone (subsequently referred to as limestone) lenses was collected from quarry exposures, road cuts, from drill holes using reverse circulation air coring techniques, and from back-hoe trenches and pits. The limestone lenses were fully excavated in four of the study sites to expose the contact between a limestone lens and underlying yellow sand. The limestone lenses were excavated in short 2 to 3 m long trenches along their bases at the other study sites with information augmented by drilling.

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The relationships between Holocene dune sand and Pleistocene units were studied by utilising aerial photographs of the region between Bunbury and Dongara, by topographic levelling to determine cross-sectional relief of Holocene dunes, and by air core drilling, augering and trenching to ascertain thickness, geometry and underlying contact relationships of the Holocene dune deposits.

Samples also were collected for petrographic analyses. This material included *in situ* yellow sand, rhizoconcretions in the yellow sand, calcreted pipes in yellow sand, general samples of friable to indurated Pleistocene limestone, and indurated (sparry calcite cemented) Holocene dune sand.

Geological Setting

The study area is the Swan Coastal Plain which is the coastal lowland stretching from Geographe Bay to Dongara (Fig. 1). The plain is bordered to the east by the Darling Plateau or by the Dandaragan Plateau and Eneabba Plain (Playford *et al.* 1976, Biggs *et al.* 1980). The seaward portion of the Swan Coastal Plain is of relevance to this study because in these locations ridges of the Pleistocene Tamala Limestone (= Spearwood Dunes of McArthur & Bettenay 1960) may interfinger with or lie juxtaposed against Pleistocene yellow quartz sand to the east, and adjoin Holocene dunes of the modern coast to the west (Fig. 1).

The Holocene coastal dune sands, referred to as Safety Bay Sand (Passmore 1970, Playford *et al.* 1976, Semeniuk & Searle 1985), typically are a short-parallel unit of white to cream calcareous quartz sand variable in width and thickness dependent upon coastal type and supply of sand. In many areas the coastal dunes form massive inland migratory parabolic systems that transgress over either earlier Holocene sand sequences or Pleistocene units such as Tamala Limestone and yellow sand.

From a subcontinental perspective it is apparent that the number, attenuation and extent of inland ingress of the Holocene parabolic dunes increase from south to north in response to a more arid climate and more intense wind system (see Fig. 2 of Searle & Semeniuk 1985). Additionally the direction of the parabolic dune axis changes progressively from approximately east-west in southern areas to north-south in northern areas (Fig. 1).

The belt of Tamala Limestone has a shore-parallel trend. The limestone may crop out at the coast, or may be buried by Holocene littoral and coastal dune deposits. The eastern margin of the Tamala Limestone at its contact with Bassendean Sand is more complicated, and is locally sharp, or marked by interfingering, or marked by a zone of lenses.

The lithofacies referred to herein as yellow sand, although typically yellow, also includes sands varying from white to orange to locally red. Yellow sand is predominantly quartz with moderate to trace amounts of feldspar, and minor kaolin, goethite, and heavy minerals (Prider 1948, Baxter 1972, Lissiman & Oxenford 1973, Glassford & Killigrew 1976, Glassford 1980). The term yellow sand as used here is strictly a lithologic term, with no implication as to stratigraphic occurrence. That is, yellow sand does not necessarily belong to any one of the currently defined Quaternary formations. As such it includes the yellow sand portions of the Tamala Limestone (or Spearwood Dunes), the Basssendean Sand, and the Yoganup Formation.

Geomorphic, Stratigraphic & Lithologic Features of Holocene Parabolic Dunes

The geomorphic and statigraphic relationships between Holocene parabolic dunes of the Safety Bay Sand and underlying Pleistocene units were investigated in 5 localities: 1) Mandurah, 2) Trigg Island, 3) Whitfords, 4) Cervantes, 5) Jurien Bay, and 6) Dongara (Fig. 1). The results of the investigations are shown in Fig. 2. The key elements of the Holocene stratigraphic information are summarised in Fig. 3.

The coastal zone of the study areas, encompassing the shoreline and the subaerial strip up to several kilometres inland, consists of an overlapping belt of dune-sand ridges developed as adjacent parabolic dunes have formed and accumulated under the influence of prevailing strong onshore winds. However, distal from the coastal zone there are isolated parabolic dunes extending up to several kilometres inland. The amount of overlap between adjacent parabolic dunes also decreases to landward (Fig. 2). In many areas the attenuated parabolic dunes have become detached from their coastal ridge source to become isolated curved ribbons/shoestrings and conical hills of aeolian sand.

Cross-sectional stratigraphic profiles indicate that in near coastal zones the aeolian ridge consists of overlapping and adjacent parabolic dunes. However to landward, as the overall inland extent of parabolic dune encroachment diminishes, individual isolated parabolic dunes are recognisable with distinct migrating rim, arms and bowl. In cross-section the individual arms of these isolated parabolic dunes appear as low sand mounds with either flat bases, or at least gently undulating bases, or gently inclined bases, corresponding to the buried topography of a broadly undulating yellow sand plain. In some areas the cross-sections show Safety Bay Sand as a thin sheet with mound-like thickenings indicating local coalescense of the parabolic dunes. Older degraded solitary parabolic dunes may be reduced to low conical sand hills (the residual parabolic dune front) with loss of the trailing arms (Fig. 4). The final product of this type of geomorphic degradation is an isolated low-relief concial mound of calcareous sand.

In most areas humic soil had developed on yellow sand and the contact of the soil with overlying white Safety Bay Sand is sharp. In some local areas however, the white Safety Bay Sand may lie directly on yellow sand without an intervening soil sheet. In pits and trenches cut into the Safety Bay Sand large scale cross layering is evident and inclined to landward indicating the direction of migration of the advancing face of the parabolic dune.

Locally, the Holocene dune sands are weakly indurated by sparry calcite cement similar to the induration described in aeolian sands elsewhere in the world (Yaalon 1967, Bathurst 1975). These cements are thin epitaxial growths on grains and are thickest at grain contacts. The cements are forming in modern vadose environments in the southwestern coastal zone (Semeniuk 1983). In the yellow sand beneath the base of the Holocene dune sands there may be local development of rhizoconcretions where calcium carbonate from solutions derived from the calcareous dunes has precipitated around plant roots lodged in the *non calcareous* yellow sand. These rhizoconcretions are typically enveloped by a halo of bleached white quartz sand. Thus in the vicinity of its contact with carbonate sand yellow quartz sand is being transformed into a quartzose limestone. There also may be root

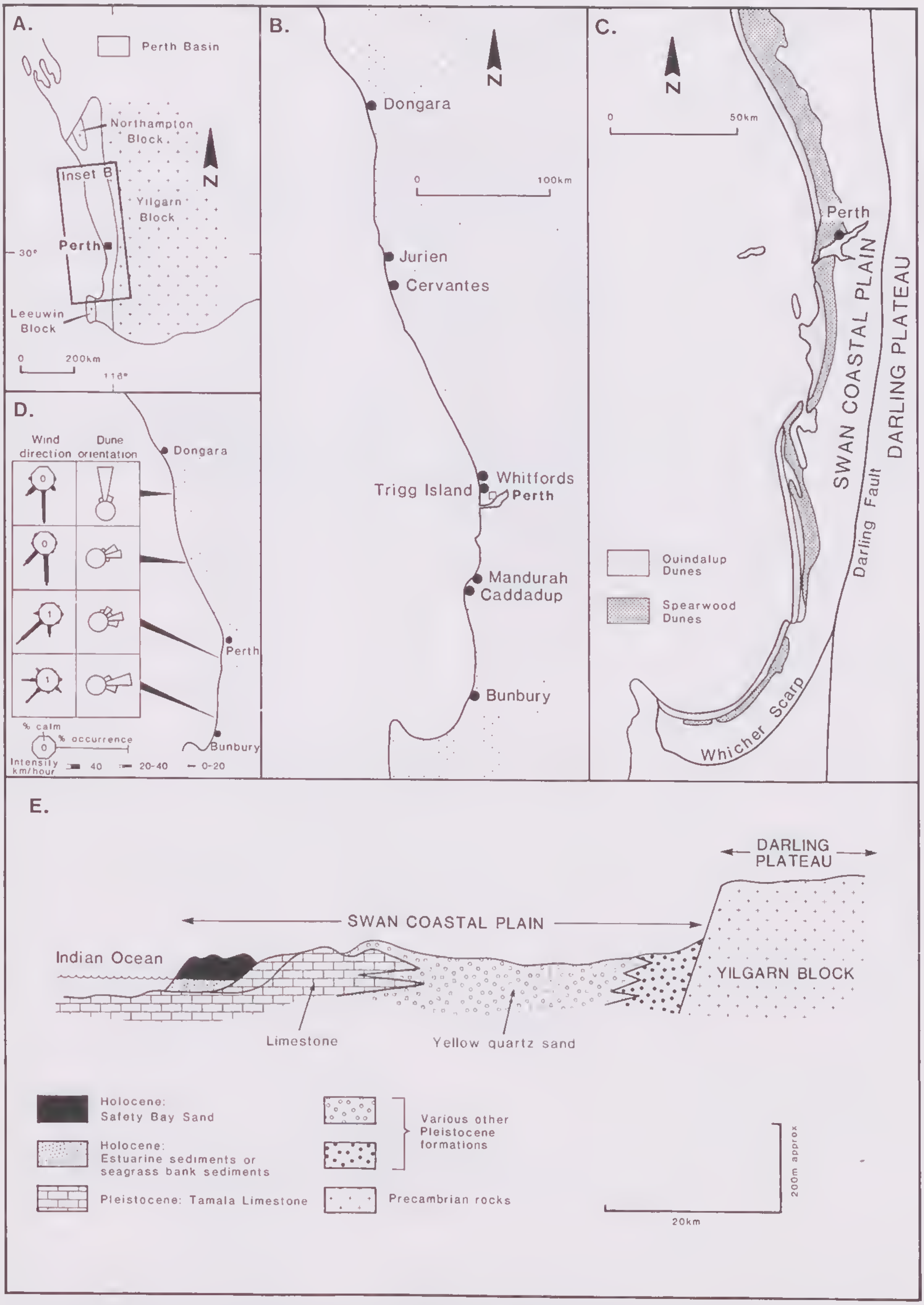

Figure 1.—Geological Setting. A Perth Basin (after Playford *et al* 1976). B Swan Coastal Plain and study sites. C Geomorphic units and shore-parallel extent of the Spearwood Dunes (after McArthur & Bettenay 1960). D Orientation of Holocene parabolic dune axes along the coastal zone (wind directions from Searle & Semeniuk 1985). E. Schematic section showing regional stratigraphic framework of the Swan Coastal Plain.

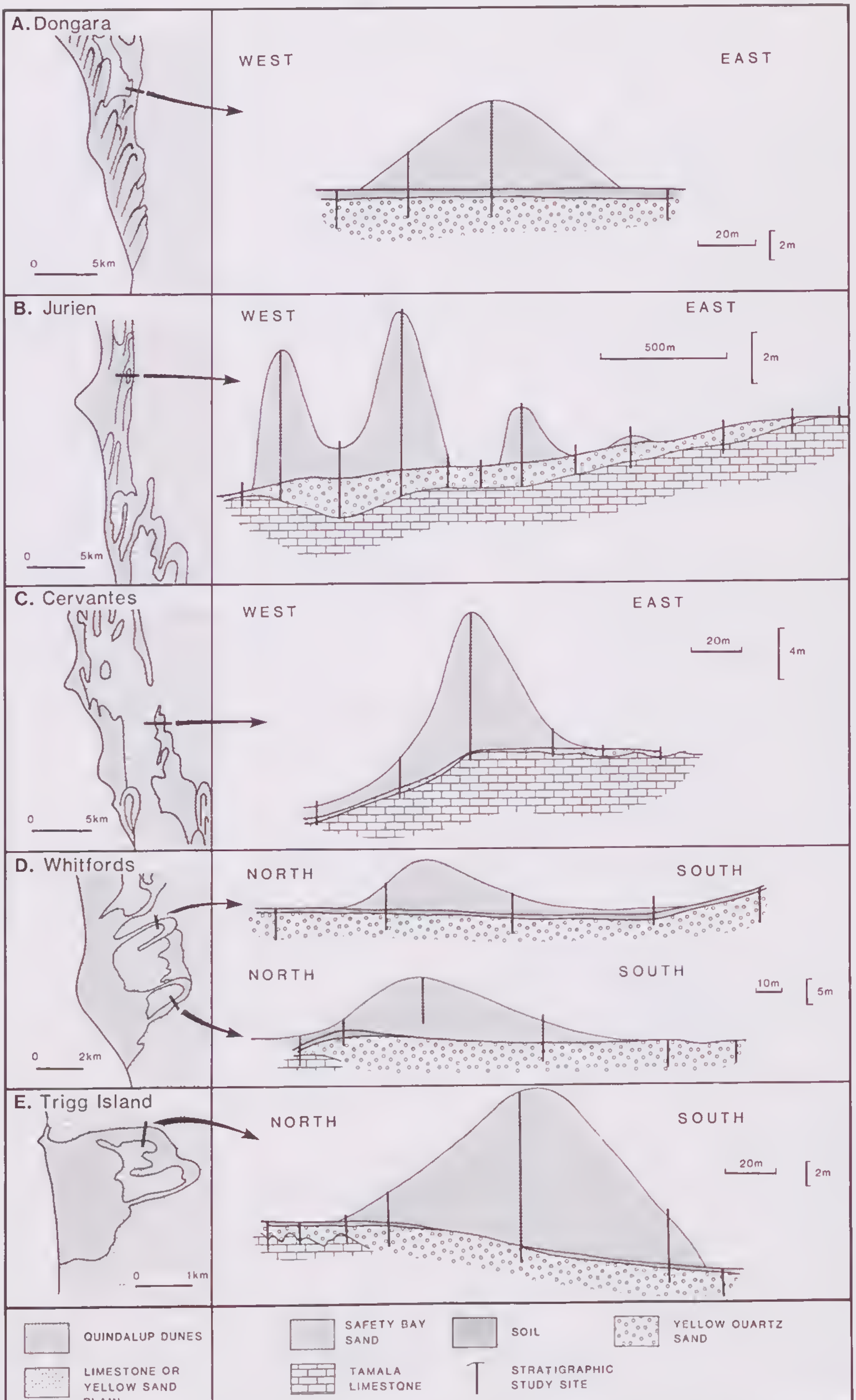

Figure 2.—Plan view and cross sections of Holocene coastal parabolic dunes showing attenuated dune forms, isolated parabolic arms, and stratigraphic profiles.

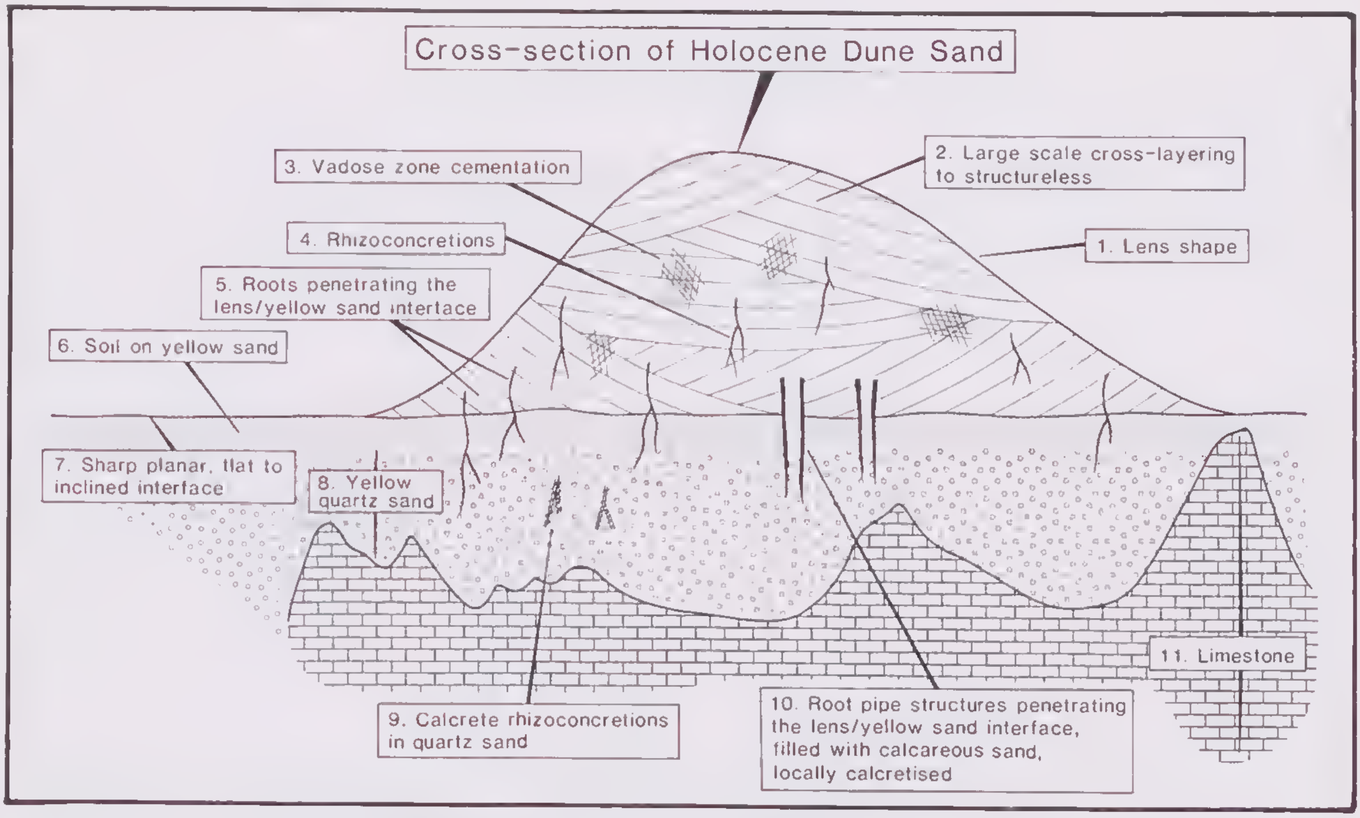

Figure 3.—Summary of key features of stratigraphic cross sections through Holocene parabolic dunes.

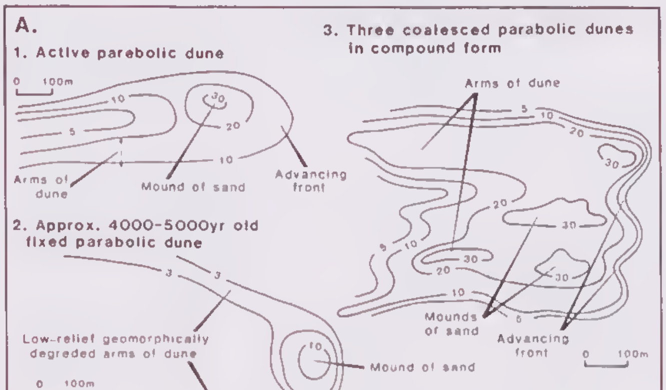

Figure 4.—A Plan view of some active and geomorphically degraded parabolic dunes. B Inferred sequence of dune evolution and degradation resulting in conical sand hills.

pipes which descend from the unlithified Holocene calcerous aeolian sand through the interface between the Holocene sand and yellow sand and into the yellow sand. These pipes are up to 20 cm diameter and are filled with calcareous aeolian sand infiltrated from above (Fig. 5).

Pleistocene Limestone Lenses in yellow sand

Limestone lenses have been studied in detail at 7 localities. The essential information on these lenses is summarized below (Figs. 6, 7 & 8):

1) The lenses are usually 2-5 m thick and up to 10 m thick; in cross-section they are up to 20-30 m wide and in places up to 150 m wide, tapering at their margins.

2) The limestone of the lens is typically aeolianite; it is cross laminated at the large scale with cross layering dipping to northeast, east and southeast, and contains abundant to common rhizoconcretions. This is important in that it is not a marine limestone that occurs as lenses. The limestone typically is medium sand-sized quartz skeletal grainstone cemented by sparry calcite typical of vadose environments.

3) The top of a lens, as defined by an enveloping surface, is convex, but in detail the top surface is sculptured by "solution" pipes and karren structures and impregnated with massive/laminar calcrete; these features are absent along the basal limestone/yellow sand interface.

4) Some of the larger lenses and lens margins have been segmented by karren structures.

5) Overall, the base of a lens is flat or semi-planar, but it is not necessarily horizontal; in detail it is flat or slightly hummocky with hummocks < 10 cm amplitude over a length of a metre; the basal contact may be modified (penetrated) by calcareous sand-filled root pipes and by yellow quartz sand-filled termite burrows.

6) The contact of limestone with underlying yellow sand is sharp and planar.

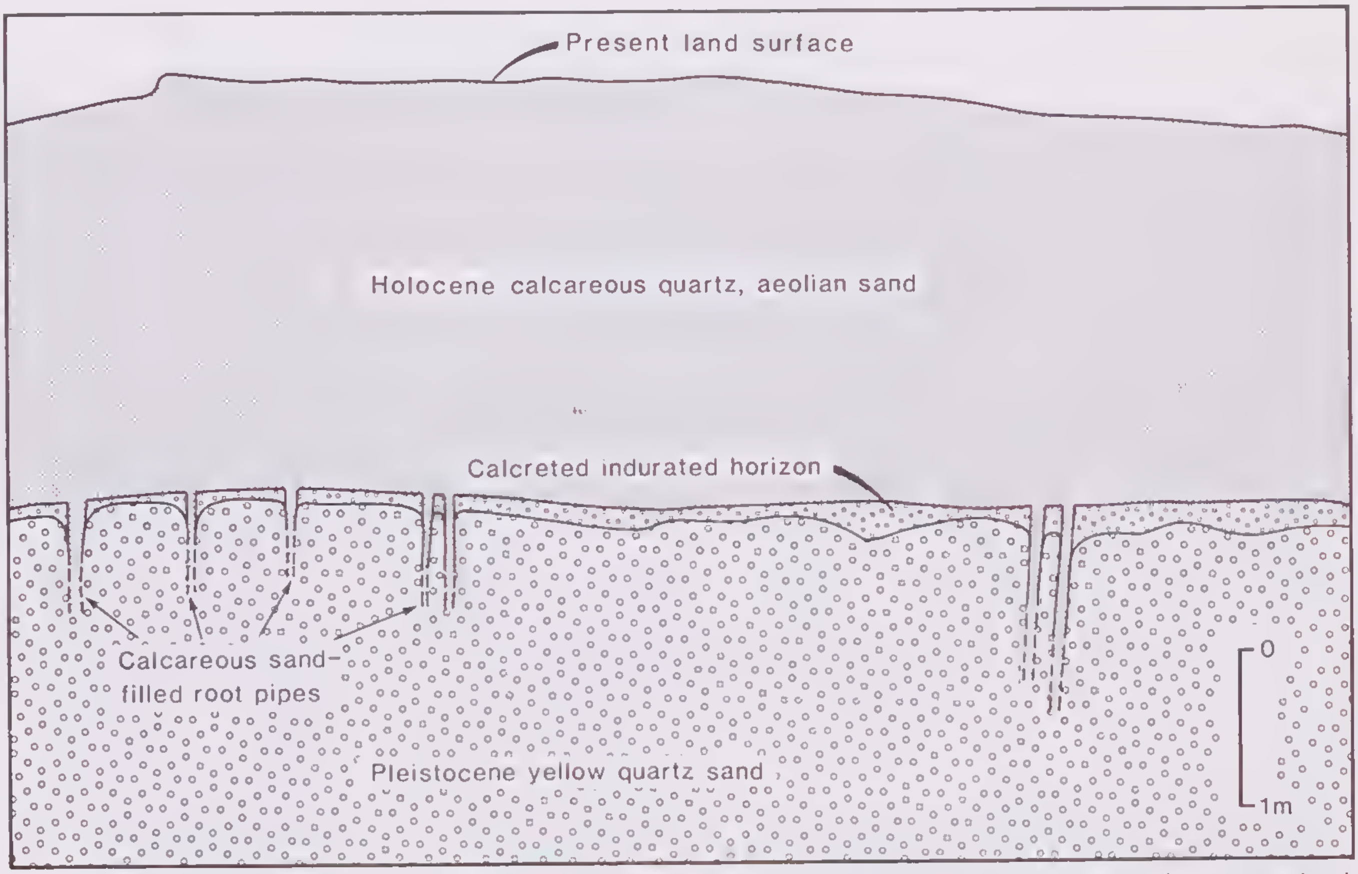

Figure 5.—Tracing from photograph showing relationship between unlithified Holocene calcareous aeolian sand and underlying yellow quartz sand in the Cervantes area. The sharp horizontal interface between them is a weak pedogenic surface, developed on the yellow sand, that has also been impregnated by incipient calcrete. The interface has been punctured by root pipes which are now filled with unlithified calcareous sand.

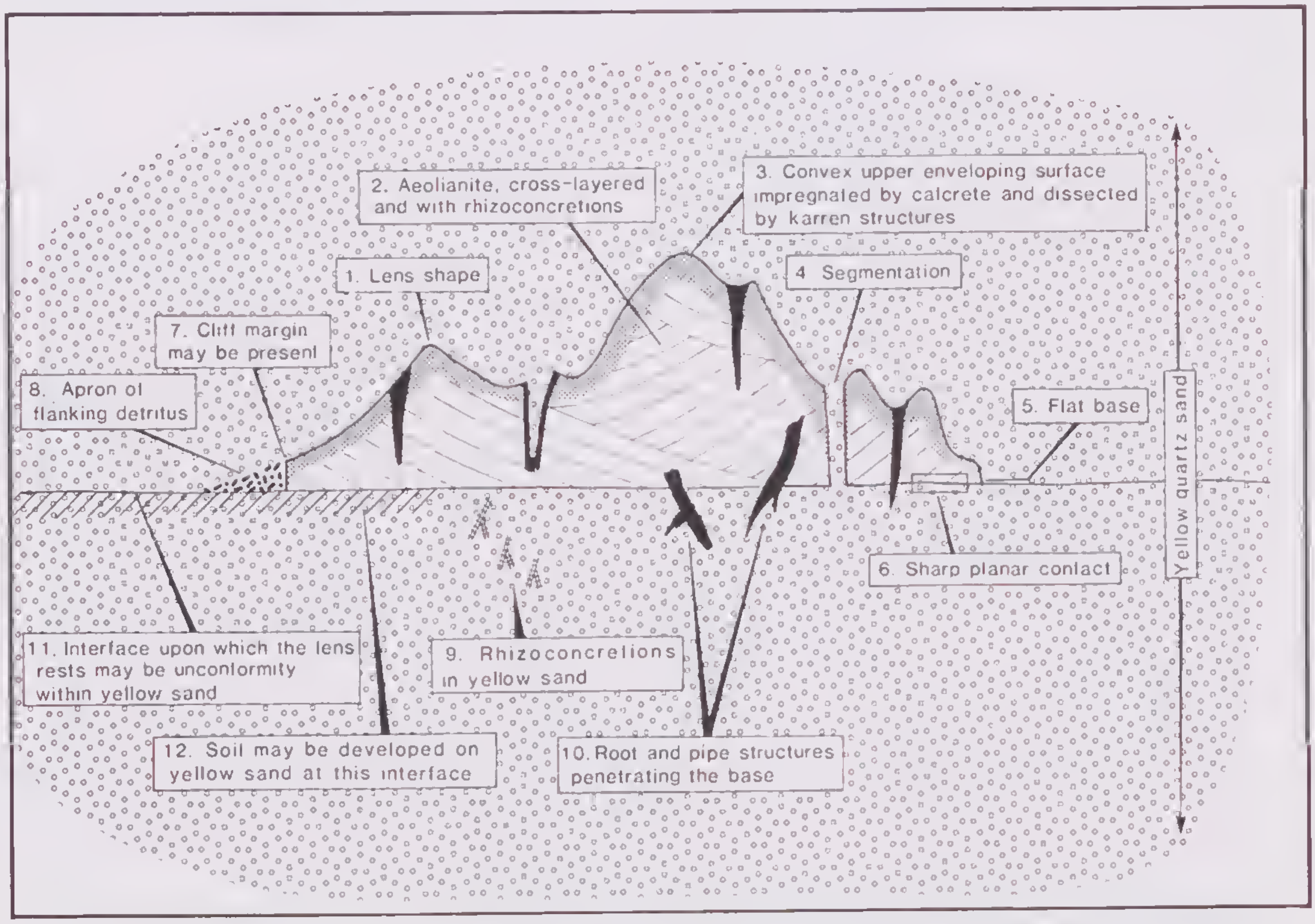

Figure 6.—Summary of key features of Pleistocene limestone lenses. Numbered annotations relate to the observations listed on pp 39-43 of text.

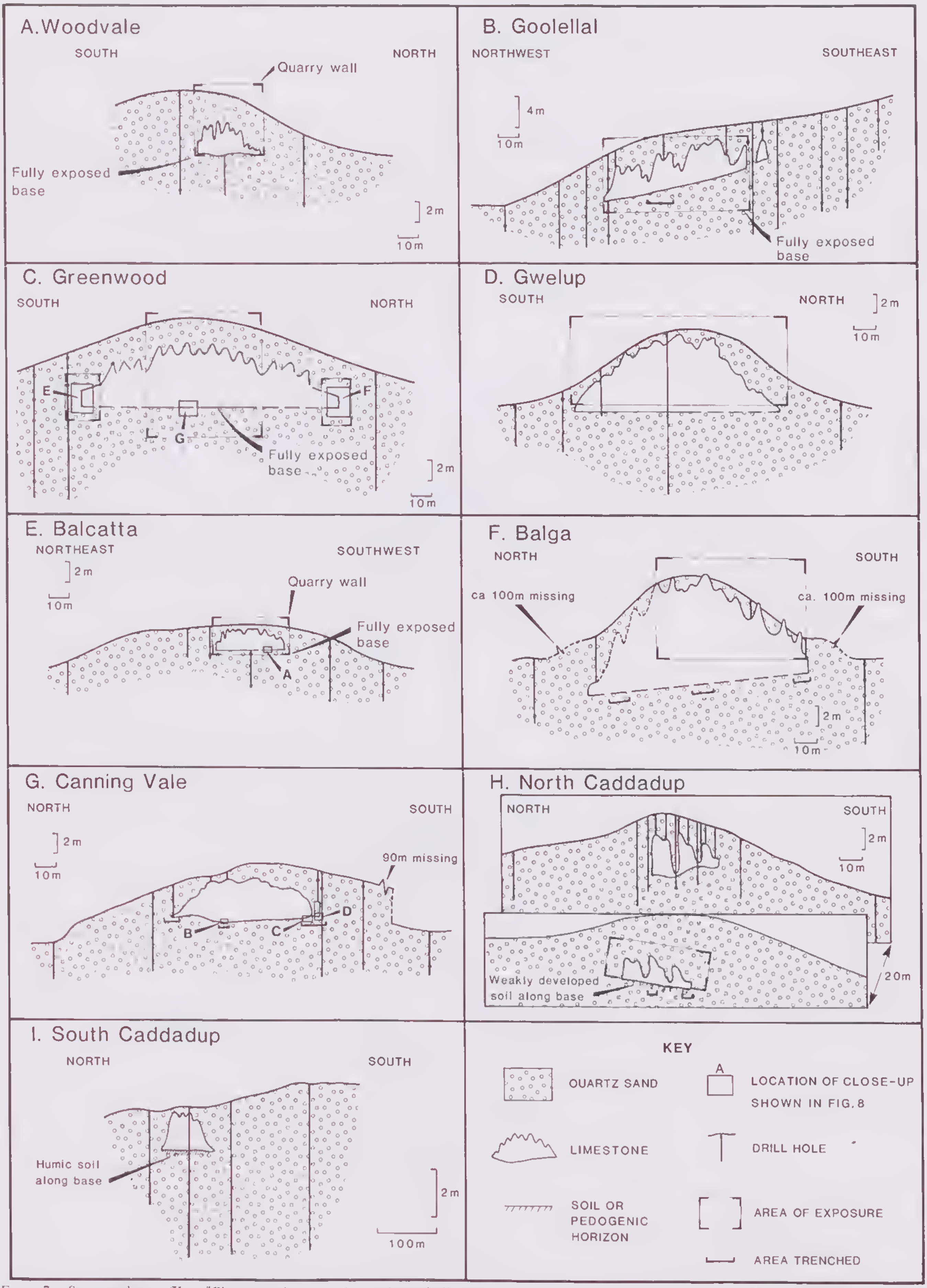

Figure 7.—Stratigraphic profiles of Pleistocene limestone lenses. Insets indicate where detail sections are illustrated in Fig. 8 Latitude and longitude locations of limestone lenses are: Woodvale 31°47′50″S. 115°48′00″E; Goolellal 31°48′20″S. 115°48′15″E; Greenwood 31°50′10″S. 115°47′50″E; Gwelup 31°52′00″S. 115°48′10″E; Balcatta 31°51′50″S. 115°48′20″E; Balga 31°52′05″S. 115°49′25″E; Canning Vale 32°04′25″S. 115°53′55″E; N. Caddadup 32°36′10″S. 115°38′10″E; S. Caddadup 32°36′30″S. 115°38′15″E.

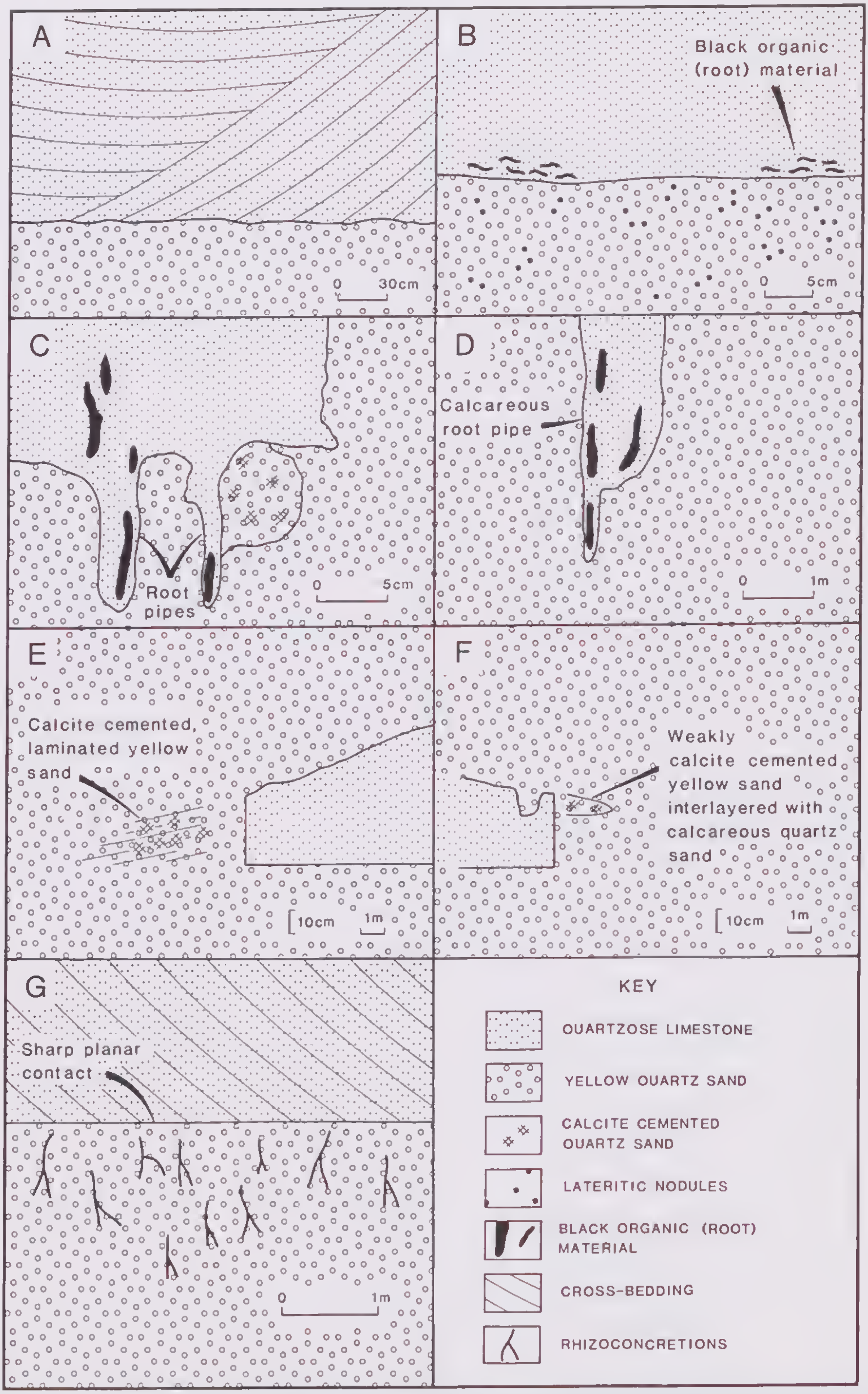

Figure 8.—Tracings from photographs showing details of stratigraphy at the contact between limestone lenses and encompassing yellow sand. **A, B & G** Planar sharp contact of base of limestone lens and underlying yellow sand. **G** Rhizoconcretions in underlying yellow sand. **C & D** Details of pipe structures penetrating the interface between limestone lens and underlying yellow sand. **E & F** Laminated apron deposit flanking a limestone lens.

7) Some lenses have cliff margins with the adjoining and encompassing yellow sand.

8) Laminated and cross laminated wedges and sheets of calcareous quartz sand interlayered with coarse and medium quartz sand form flanking aprons, 30-50 cm thick and several metres wide, around some lenses.

9) Calcareous rhizoconcretions cementing the yellow quartz sand may occur immediately below the limestone: these rhizoconcretions, consisting of calcrete and sparry calcite, impregnate a grain-supported yellow quartz sand; goethite pigmented (yellow) kaolin coatings on the yellow quartz grains are enveloped by the calcite cements.

10) The yellow sand immediately below the limestone lens may be penetrated for a limited distance (20-50 cm up to 1 m) by root casts and root pipes emanating from the limestone and they may be 1 cm, 10 cm or 20 cm in diameter, and be filled with calcareous sand infiltrated from the lens.

11) The limestone lens may directly overlie an unconformity, or bounding surface (see Talbot 1985), within the yellow sand marked by an extensive horizon of leached white sand, or coarse sand, or a pedogenic surface of clayey yellow sand or lateritic yellow sand.

12) Locally, the limestone lens rests on a humic soil developed on yellow sand.

The significance of each of the above observations on Pleistocene limestone lenses is presented in Table 1.

Table 1

Significance of the geological information on the limestone lenses

Observation	Interpretation	Significance
1. lens shape of limited size	mound-like sand body which, after lithification to limestone, would have resembled a limestone knoll	geometry of body reflects geometry of depositional form
2. internal structure of cross layering and rhizoconcretions, aeolianite lithology	typical aeolian accumulation and post depositional diagenesis	aeolian origin of the body and normal post-depositional diagenetic processes have operated
3. top of lens with pipes, karren structures and calcrete	solution modification of exposed surface or shallowly buried surface; root penetration to develop pipes; subaerial calcretization of surface of limestone	limestone lens had undergone alteration in subaerial environment, the top surface *not* the basal surface, has been modified subaerially
4. segmentation by karren structures	karren structures propagating downwards locally dissected the lenses	dissection results in steep-sided hollows and ultimately can result in cliff edges to the limestone lenses
5. flat base	aeolianite body encroached onto a sand plain	the contact between the limestone and underlying sand is depositional *not* solutional
6. sharp planar contact between limestone and underlying yellow quartz	aeolianite body encroached onto a sand plain with subsequent modification of contact by bioturbation	the contact is not solutional; small scale irregularities are due to vegetation and fauna effects
7. cliff margins to lenses	during weathering/erosion in the subaerial environment the lenses were undercut on their margins; undercutting may be due to solution at the quartz sand/limestone contact or to wind removal of adjoining/underlying quartz sand	typical expression of upstanding limestone bodies (or knolls) when underlain by non-calcareous materials, i.e. sharp vertical small to large cliff edge, not thinly tapering
8. aprons of detritus	residual quartz from subaerial solution and the more resistant carbonate grians accumulated as aprons around the limestone knoll	the margins of the lenses were subaerially exposed and the lenses (knolls) were exposed; only subsequently was the entire knoll and apron system buried by later influx of yellow quartz sand; overlying sand emplaced by transportation and is not the product of *in situ* decalcification.
9. calcareous rhizoconcretions in underlying quartz sand	carbonate dissolved from the limestone percolated through the vadose zone located in the limestone and underlying yellow quartz sand; plant roots utilising the vadose water precipitated rhizoconcretions in the limestone and in the underlying quartz sand	source of carbonate in the quartz sand is from overlying limestone; rhizoconcretions post-date emplacement of limestone onto yellow quartz sand.
10. penetration of the basal limestone/yellow sand contact by plant root structures and pipes filled with quartz carbonate sand	vegetation inhabiting the knolls emplaced their roots through the limestone, through the limestone/yellow sand interface, and into the yellow sand; later infiltration of calcareous quartz sand into the rotted roots developed the various sized pipes; the calcareous structures were subsequently calcretised	the limestone/yellow sand contact can be modified by plant root activity, however the overall lower contact between limestone and yellow sand is essentially planar
11. limestone rests on an unconformity	aeolianite body encroached onto quartz sand plain whose surface was pedogenically altered (i.e. bounding surface)	the lower limestone/yellow sand contact is depositional and not solutional
12. limestone rests on humic soil	aeolianite body encroached onto quartz sand plain whose surface was pedogenically altered	the lower limestone/yellow sand contact is depositional and not solutional

*Observations numbered 1-12 follow that in the text pp 39-43.

The cross-sections illustrated in the figures represent opportunistic profiles through lenses as exposed in quarries and determined by coring. Thus the cross-sections may represent only the margin of larger lenses, or may represent oblique profiles through elongate lenses (*e.g.* sites D & G). However in some locations (site C, E & H) the lenses were observed in entirety and the sections represent maximum width and thickness of a lens.

Interpretation of Pleistocene sequences

Many of the features described from Pleistocene sequences are direct equivalents of lenses of aeolian coastal sand (arms or rims of isolated parabolic dunes) overlying quartz sand sheets as described in the modern coastal setting.

Local palaeo-environmental interpretation

The Pleistocene limestone lenses are interpreted as geomorphic residuals of calcareous parabolic dune fronts and as cross-sections of the arms of parabolic dunes, or locally developed barchan dune bodies resting on a former yellow sand plain. Generally it appears that during the Pleistocene the aeolian sand encroached onto a yellow sand plain but locally, particularly in more humid southern areas, the aeolian sand encroached onto a yellow sand plain which had a soil profile. The calcareous dunes migrated from the coastal zone as attenuated parabolic forms and locally became detached from their source. At this stage a detached dune could develop into a small barchan. As such in a cross-section parallel to the coast the detached dunes now appear as flat-based lenses. Internally, the large scale cross layering in the lenses indicates gross landward migration.

Vadose zone cementation transformed the calcareous aeolian sand to limestone. Small scale (grain to grain) solution of calcium carbonate by meteoric water (Yaalon 1967, Bathurst 1975), the translocation of dissolved carbonate to levels lower in the vadose profile, and the utilisation of vadose water by plants resulted in the development of carbonate rhizoconcretions in the aeolian sand *and locally in the underlying yellow quartz sand.*

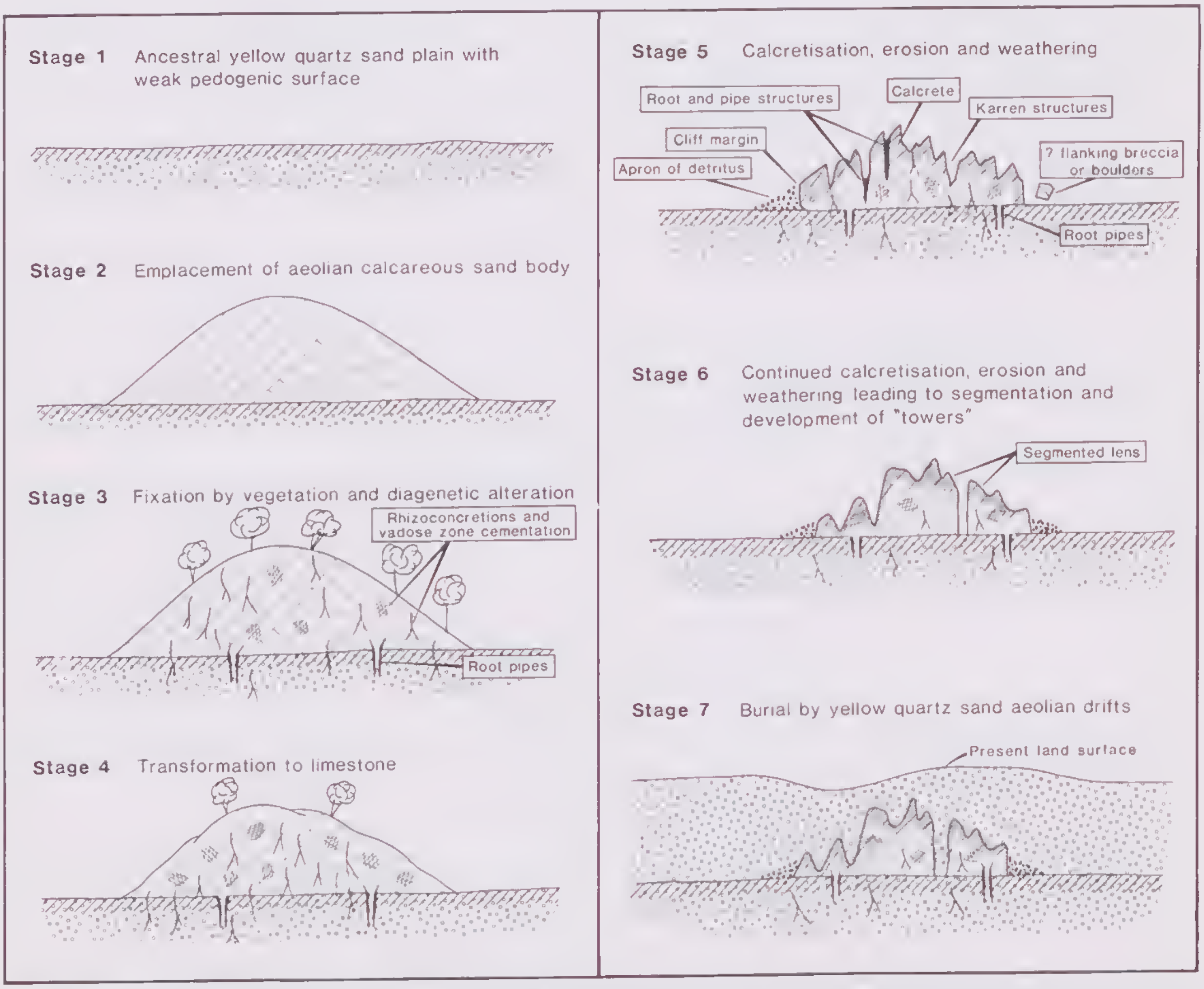

Figure 9.—Model depicting origin and stages in the alteration of limestone lenses. Note that burial by aeolian yellow quartz sand can take place at any stage and consequently terminate any further development of alteration stages. In addition, aeolian erosion may also exhume the limestone lenses and thus reinitiate the alteration sequence.

The limestone lenses have undergone subaerial weathering, subaerial solution, erosion and impregnation with calcrete. This resulted in a general overall cross-sectional volume reduction of the lens, in development of solution features such as karren and lapies structures (Bogli 1960, 1961, Jennings & Sweeting 1963, Sweeting 1972, Jakucs 1977, Estaban & Klappa 1983), and in development of a calcrete capstone. Larger scale subaerial solution and development of karren structure markedly modified the convex upper surface of the limestone to a series of steep-sided pinnacles and locally dissected the limestone lenses to an extent that the lenses become segmented. The segmented components would resemble miniature karst towers as described by Jakucs (1977). The inferred weathering/erosion history of the lenses is illustrated in Fig. 9. The features of the upper contact between limestone and yellow sand will be the subject of another paper.

Locally, cliff margins and perhaps flanking boulder/block deposits were developed where the limestone lens was undercut by wind deflation or rain wash of yellow sand, and collapsed along a cliffline. Weathering and sheet wash also resulted in the development of aprons, composed of quartz sand and resistant carbonate grains, both derived in part from the limestone, flanking the margins of lenses. Similar solution structures in subaerially exposed limestone and flanking detrital deposits derived from limestone outcrops, occur in semiarid to arid regions elsewhere (Jakucs 1979).

At all stages of weathering and erosion, the basal contact of the calcareous sand/limestone lens with underlying yellow sand was continually modified by vegetation roots and burrowing fauna such as termites. This resulted in infiltration of calcareous sediment *down* into the yellow sand via plant root holes and animal burrows, and in the translocation of yellow sand *up* into the calcareous sand or limestone via termite activities.

Coastal setting interpretation

The relationship between the major limestone ridges of the Spearwood Dunes and the outliers of limestone lenses represents a transition from a coastal zone to inland, essentially a coastal to continental transition. The Pleistocene coastal environment generated massive aeolian sand accumulations that developed as a large ridge. The ridge consisted of an overlapping series of parabolic dunes. This coastal dune ridge overlies an unconformity on limestone or on yellow sand (see Fig. 5 in Allen 1981). Further to landward the ancestral terrain would have consisted of limestone or yellow sand plain.

Staggered advances of discrete parabolic dunes emanated from the coastal zone and encroached onto the adjoining ancestral hinterland terrain. These parabolic dunes extended up to several kilometres from their source and locally became detached. As such they represent the extremities of the influence of coastal environment sedimentation.

Gross stratigraphic interpretation

The stratigraphic relationship of limestone lenses in a regional setting represents a transition zone between two major lithofacies, a marine derived coastal carbonate facies, and a land derived continental yellow quartz sand facies. Such a setting is not unusual in the geological record: as Glennie (1970: 121) points out "it is important to realise that continental (desert) shoreline and marine facies may all occur in close proximity".

The gross stratigraphic setting of this coastal region is interpreted as one of periodic yellow sand incursions from the east by aeolian transport during glacial periods associated with aridity and lower sea levels, alternating with coastal aeolian building during interglacial periods (following Fairbridge 1964, Kukla 1977, Sarnthein 1978, Sprigg 1979, Glassford 1980) associated with wetter climates and elevated sealevels. Thus during glacial-age desert phases yellow sand incursions would have extended onto the exposed continental shelf.

During an interglacial the sediments of the shoreline environment were composed of sand derived from reworking of the former sand plain (quartz and some felspar), reworking of pre-existing limestone ridges (lithoclasts) and contribution of resident/nearby fauna (skeletons). The quartzose calcareous sand was piled into a dune ridge along the Pleistocene shoreline. From this main ridge parabolic dunes extended inland forming isolated arms and mounds of quartzose calcareous sand. Later, induration by calcite cementation converted these aeolian sands to limestone.

During the ensuing glacial period yellow sand aeolian drifts blanketed the entire coastal zone burying the limestone lenses and the main limestone ridge. Since its last major mobilisation the yellow sand has been variously podzolized, bioturbated and locally reworked by aeolian, fluvial, lacustrine and marine processes.

The stratigraphic array and the dynamics of the gross system is interpreted as an interacting and alternating system of desert aeolian sand influx (following Killigrew & Glassford 1976, Glassford & Killigrew 1976, Glassford 1980) and marine (coastal) reworking. The model is summarized in Fig. 10. Successive alternating episodes of desert aeolian influx and marine reworking would result in a thick section of yellow quartz sand on the east portion of the Spearwood (limestone) ridges with scattered limestone lenses within the yellow sand body.

The zone of limestone lenses in a given time interval would represent the transitional zone between coastal dunes and ancestral hinterland where local coastal aeolian incursions penetrated a limited extent to inland (for analogous topographic and coastal settings see Glennie 1970, Fryberger & Ahlbrandt 1979 and Fryberger *et al.* 1983). As such the contact between limestone ridges and hinterland yellow sand (i.e. between Tamala Limestone and Bassendean Sand) may not necessarily be a straight north-south junction. Rather, it will be an irregular to disjointed contact, and in many places the contact will be a transitional zone of lenses.

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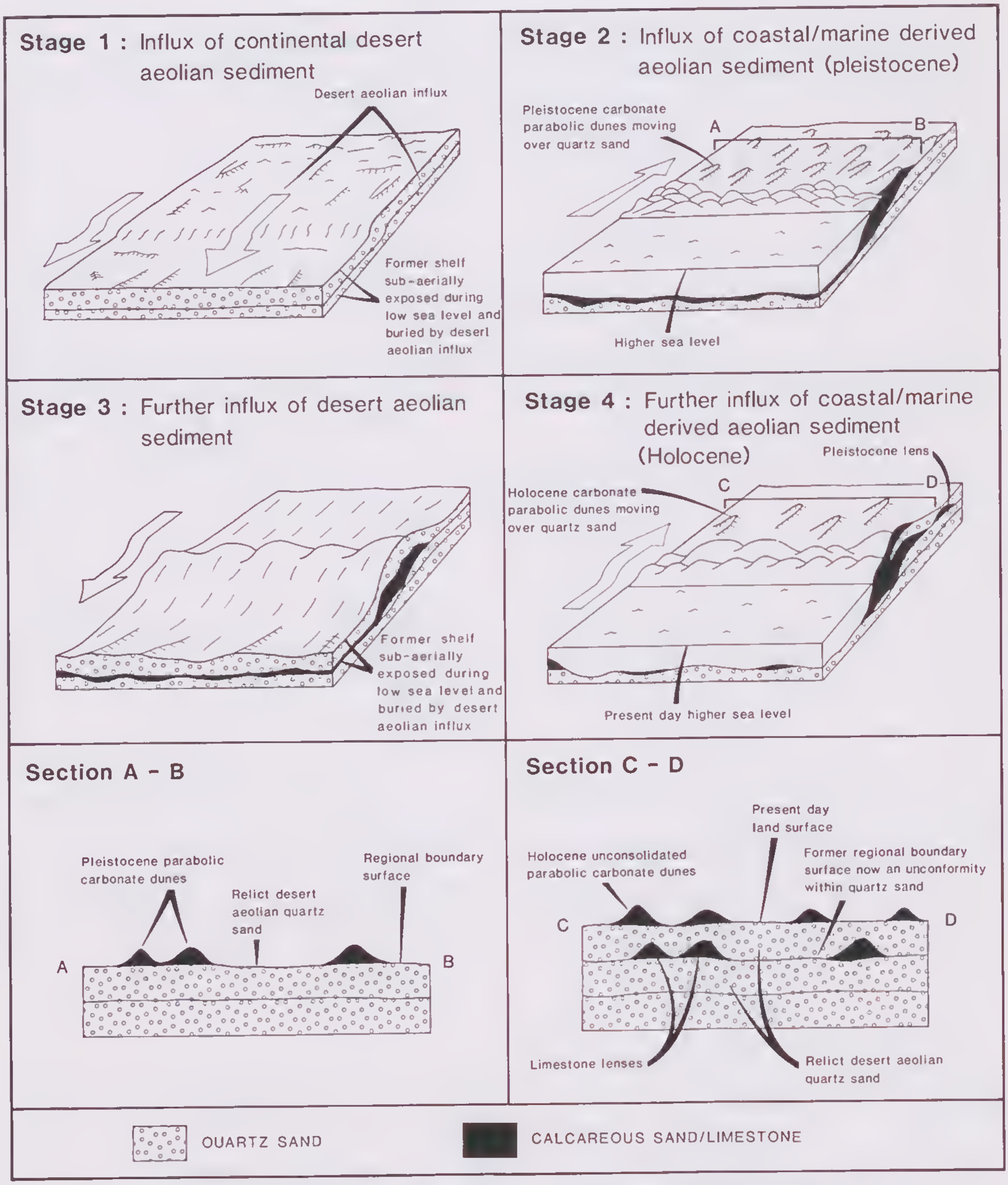

Figure 10.—Model depicting alternating phases of desert aeolian influx during glacial periods and coastal dune accumulation during interglacial periods. Limestone lenses reflect the transition zone between coastal aeolian accumulations and the continental aeolian facies.

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The Unconformity in the Kelly Belt, east Pilbara Craton

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Abstract

The approximately 3 Ga year old unconformity of the Whim Creek Group and other pre-Mt Roe Basalt sequences on older rocks, in particular on banded iron formations (BIFs) of the Gorge Creek Group, is now generally accepted, being recorded in most of the greenstone belts of the Pilbara Craton. However, recent studies indicate that it occurs only as far south and east as the Marble Bar and Coongan Belts which flank the Corunna Downs and Mt Edgar batholiths. In the Kelly Belt, to the east of these batholiths, the unit previously mapped as the Lalla Rookh Sandstone (incl. Budjan Creek Formation) equates instead to the Corboy Formation, which is at the base of the Gorge Creek Group in the East Pilbara. These clastic sediments grade up into, and form an unbroken sequence with, the BIFs of the Paddy Market (Cleaverville) Formation of the Kelly Belt. They are thus assigned to the Soansville Subgroup, which can now be used synonymously with the term Gorge Creek Group. The basal clastics are also tentatively correlated, because of similarities in the sequence, to parts at least of the Mosquito Creek Formation further to the east.

Mafic volcanics do occur elsewhere in this grouping but the choice of the type section for a basalt in the Soansville Subgroup, near Charteris Creek in the Kelly Belt, is inappropriate because there this basalt underlies the unconformity and is part of an unbroken sequence of pillowed volcanics, cherts and thin tuffaceous sediment bands, frequent in the Salgash and the Talga Talga subgroups.

Introduction

Stratigraphic subdivisions of the Marble Bar area where established by Lipple (1975) and partly revised and extended by Hickman (1983) to the whole of the northern exposed part of the Pilbara Craton. Following earlier workers such as Maitland (1908) and Noldart & Wyatt (1962), Lipple (1975) had subdivided the layered sequence into a lower, Warrawoona Group, dominantly of volcanic origin and an upper, Gorge Creek Group, essentially of sedimentary rocks. The latter was subdivided into a lower, Soansville Subgroup and an upper, unnamed part which included the Lalla Rookh Sandstone, the Bunjan Creek formation, and the Mosquito Creek Formation. Like previous authors, Lipple recorded unconformities at the base of these three formations in some localities though Hickman (1983, p. 105) considered these to be of local significance only.

Fitton *et al.* (1975), from studies in the West Pilbara between Roebourne and Wodgina, restricted the term Gorge Creek Group to what would appear to equate to Lipple's Paddy Market Formation (or the Cleaverville Formation of Ryan & Kriewaldt 1964) which is part of the Soansville Subgroup (see Table 1). This formation is characterised by the developments of thick cherts, chertified sediments, BIFs (banded iron formations), and in places shales. Fitton *et al.* recognized a hiatus and regional unconformity between this unit and the overlying sequences which they estimated (1975, figure 1) from available geochronological data to have occurred about 3 Ga

Table 1

Archaean layered succession of the Pilbara (names referred to in text). Amended after Fitton *et al.* (1975), Lipple (1975), and Hickman (1983). (Geochronology, see Blake & McNaughton 1984 and Trendall 1983).

Mt Bruce Supergroup	Mt Roe Basalt	
	Regional unconformity (about 2.8 Ga)	
	Negri Volcanics ← (?)	Basalt (Yarrie Sheet area)
	(including un-named sediments and the Loudon Volcanics) ← (?)	Lalla Rookh Sandstone
	Local unconformity	
Whim Creek Group	Mallina Formation (includes the Rushall Slate and un-named acid volcanics)	
	Constantine Formation	
	Mons Cupri Volcanics	
	Warrambi Basalt	
	Regional unconformity (about 3 Ga)	
Gorge Creek Group = Soansville Subgroup	Mosquito Creek Formation	
	Honeyeater Basalt (excluding units mapped on Yarrie Sheet area)	
	Paddy Market (Cleaverville) Formation	
	Charteris Basalt (Excluding type section area)	
	Corboy (Budjan Creek) Formation	
	Regional unconformity	
Warrawoona Group	Salgash Subgroup	
	Duffer Formation (3.4 to 3.5 Ga)	
	Talga Talga Subgroup	

years ago. Available geochronological results for the whole of the Pilbara Craton are now summarized by Blake & McNaughton (1984) and by Trendall (1984). Fitton *et al.* named the sequences above the hiatus, the Whim Creek Group and the Negri Volcanics. The Whim Creek Group contained a volcanic province and a clastic province. Sediments of the latter (the Constantine Sandstone and the Mallina Formation) were equated, although not always specifically by name, to the upper, un-named part of Lipple's Gorge Creek Group; the unconformity in the West Pilbara was equated to those recorded at the base of the Lalla Rookh Sandstone, the Bunjan Formation, and the Mosquito Creek Formation.

Hickman (1977; 1983, pp. 19 & 105) denied the validity of the regional hiatus and unconformity but this was however refuted by Horwitz (1979) and Horwitz & Guj (1986). Also, both Wilhelmij & Dunlop (1984) and Krapez (1984) have mapped in detail, and recorded breaks with angular relationships, basal to the Lalla Rookh Sandstone or its equivalent, in parts of the Strelley area and in the Lalla Rookh Syncline. Horwitz & Guj (1986) pointed out that this break exists throughout the Goldsworthy and the Shay Gap belts, between what Hickman (1983) assigned to the cleaverville (Paddy market) Formation and to the Lalla Rookh Sandstone, justifying it thus as a regional feature. In these areas as well as in the syncline 3 km east of Coppin Gap in the Marble Bar Belt. Hickman (1983, p. 1 & 2) did not recognize the unconformity and interpreted volcanics and sediments above the unconformity for the Honeyeater Basalt, which, in the type section of Lipple (1975, Table 1), is below the unconformity. In effect, all these units of the Yarri and northern Port Hedland sheet areas compare well with sections above the unconformity in the Whim Creek Belt, for instance with those of the north flank of the Mt Ada-Mt Wilgie inlier, 15 km south of Roebourne (correctly mapped by Archer, 1979, although this author incorrectly placed these units below the Cleaverville Formation in his legend).

I have since also recognized the unconformity above the Soansville Subgroup in the Coongan Belt, south of Glen Herring, and in the Marble Bar Belt, south of Eginbah. Boulter *et al.* (1987) record its presence in the Tambina complex.

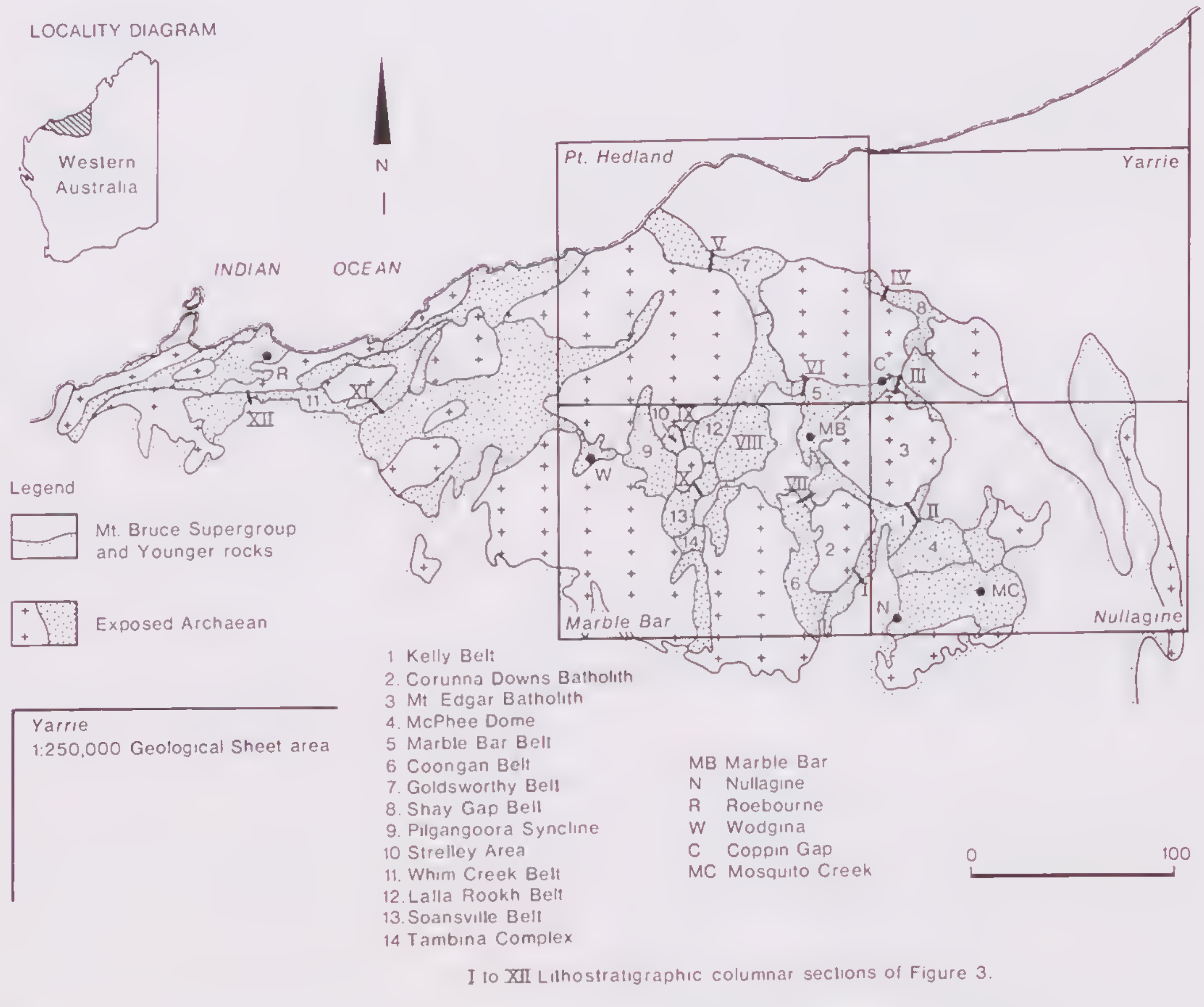

Figure 1 Structural units of the northern (exposed) Pilbara Craton (amended after Hickman 1983), and localities mentioned in the text.

In conclusion, the Soansville Subgroup is characterised in parts by the presence of thick units of cherts, chertified sediments, BIFs and shale which have been variously referred to as the Cleaverville Formation (Ryan & Kriewaldt 1964, Hickman 1983), the Paddy Market Formation (Lipple 1975, Hickman & Lipple 1978), and the Gorge Creek Group (Fitton *et al.* 1975, Horwitz 1979). An unconformity, or disconformity, estimated at about 3 Ga years, above the Soansville Subgroup, is recorded nearly everywhere west and north of the Corunna Downs and Mt Edgar Batholiths (Figure 3). An unconformity at a lower stratigraphic level was also noted by Lipple (1975) at the base of the Corboy Formation (the basal unit of the Soansville Subgroup); but this feature was also considered to be of localized extent by Hickman & Lipple (1973, p. 3). An unconformity is however recorded by Krapez (1984) in the Lalla Rookh Syncline and by Wilhelmij & Dunlop (1984) in both the Pilgangoora Syncline and the Strelley area at, what these authors consider to be, the base of the Soansville Subgroup equivalent. Figure 3 records most sections where an uncomformity or discomformity, basal to the Soansville Subgroup, was observed.

The unconformity of the Kelly Belt

The Kelly Belt passes some 25 km west of Nullagine in the East Pilbara. It flanks the Corunna Downs and Mt Edgar batholiths to the east and southeast. The belt is split in two by a syncline of overlying Mt Bruce Supergroup units (Figs 1 & 2), oblique to the greenstone belt, and the overlap of these rocks also limits the belt at both ends. The northern part is bound in the southeast by a faulted contact against Warrawoona Group units of the McPhee Dome. Most of the southern half of the belt is on the Marble Bar Geological Sheet area, mapped by Hickman & Lipple (1978), and the northern half is on the Nullagine Geological Sheet area, mapped by R Thom, A H Hickman & R J Chin (in Hickman, 1978). The Kelly Belt was also mapped by Barley (1980).

Noldart & Wyatt (1962, p. 102) recorded a stratigraphic break (in effect an angular unconformity intruded by acid igneous rocks) in the southern half of the belt, between their Budjan Creek Formation and their underlying Warrawoona succession. Many authors have equated this unconformity with the one above the Soansville Subgroup (Lipple, 1975; Fitton *et al.* 1975; Hickman & Lipple, 1978; and Hickman 1983). In the northern part of the Kelly Belt on the Nullagine Sheet area, an angular unconformity is also mapped and Hickman (1983) has attributed it to the same unconformity, namely the one above the Soansville Subgroup and he has named other units in the sequence accordingly.

I examined sections in detail, in the northern part of the Kelly Belt between the Corunna Downs Batholith and the McPhee Dome. Traverses were made along both branches of the upper reaches of Sandy Creek between the Northern Highway and an area about 2 km past the divide into

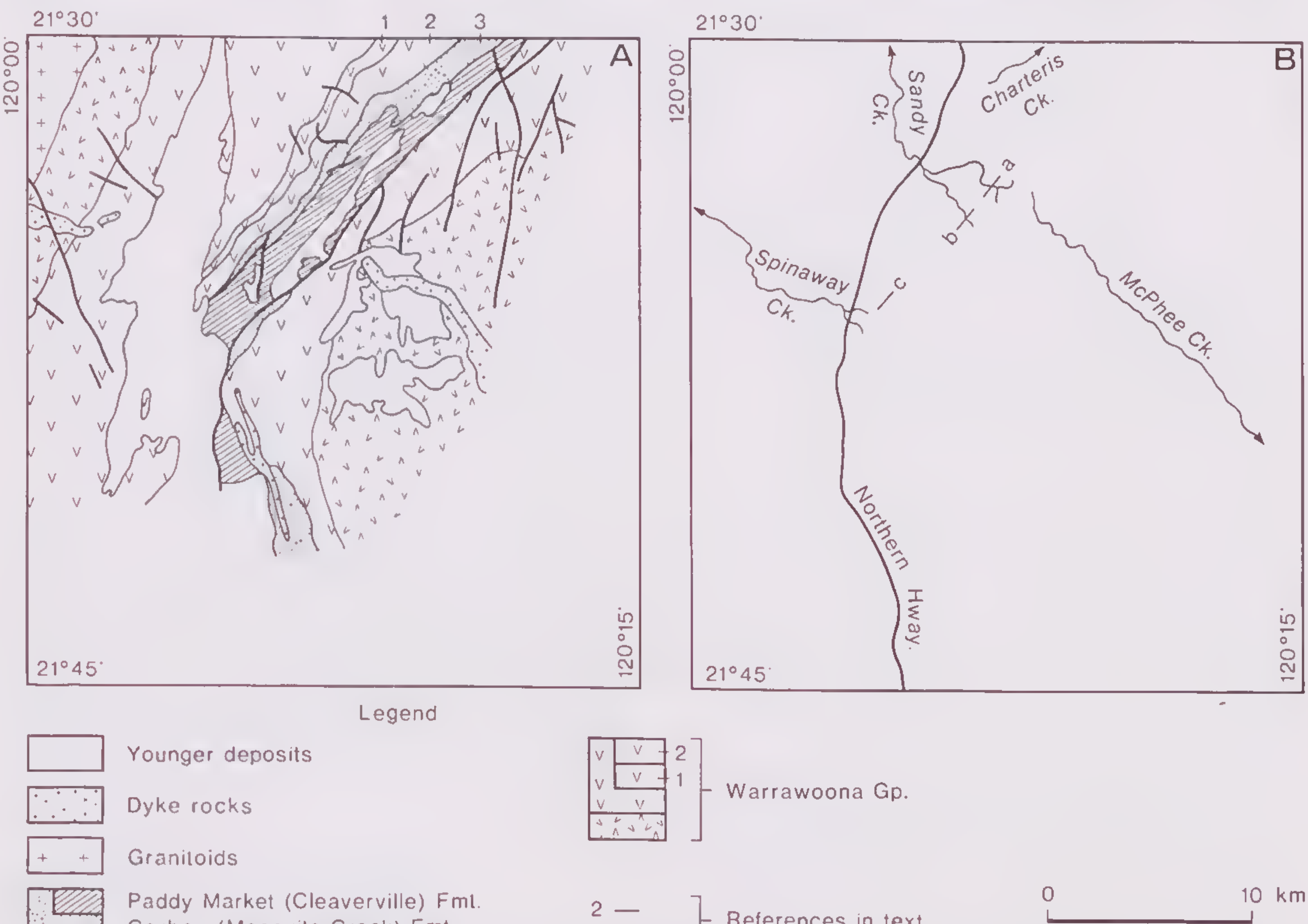

Figure 2 Kelly Belt, Sandy Creek—McPhee Creek area. **A** Geological map, amended after Thom *et al.* in Hickman (1978). **B** Map showing sections referred to in the text.

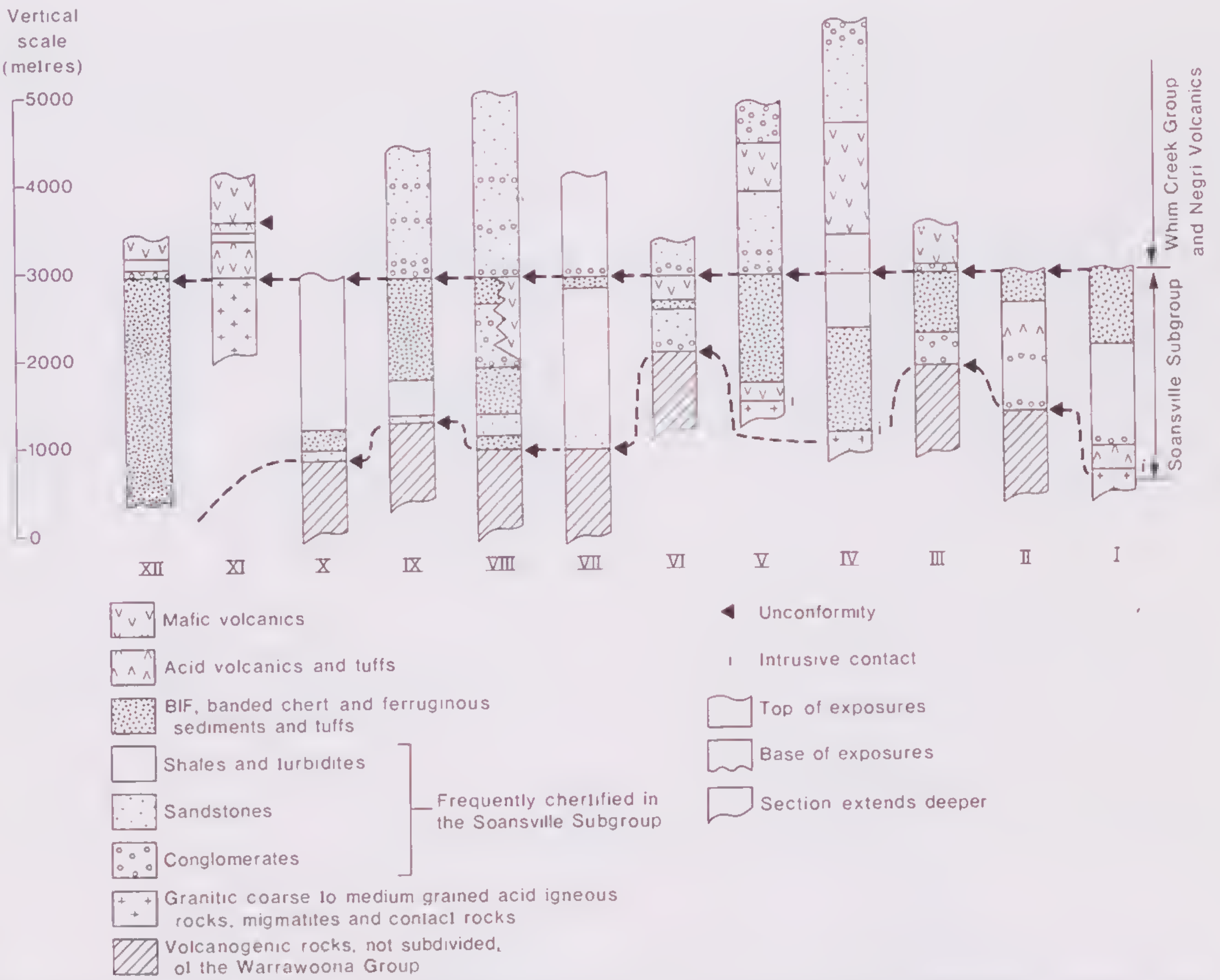

Figure 3 Measured lithostratigraphic columnar sections of selected traverses made in the Soansville Subgroup and adjoining units of the Pilbara Craton. Sills of mafic and acid rocks are not shown. The approximate location of each section is indicated on Figure 1.

(i) Southern Kelly Belt, north of Spinaway Creek.
(ii) Northern Kelly Belt, Sandy Creek.
(iii) Eastern Marble Bar Belt, east of Coppin Gap.
(iv) Shay Gap Belt, south of Shay Gap township.
(v) Goldsworthy Belt, south west of Goldsworthy township.
(vi) Western Marble Bar Belt, south of Eginbah.
(vii) Northern Coongan Belt, southeast of Glen Herring Pool.
(viii) Southwestern Lalla Rookh Syncline. Composite section, simplified from Krapez (1984, Fig. 2).
(ix) Strelley Area. Simplified from Wilhelmij & Dunlop (1984, Fig. 6).
(x) Mid-northern Soansville Belt. The upper half is derived from Hickman & Lipple (1978, geological map).
(xi) Eastern Whim Creek Belt, west of Red Hill.
(xii) Western Whim Creek Belt, south of Roebourne.

the McPhee Creek drainage. A composite lithostratigraphic columnar section is shown in Figure 3. Sections were also examined in the upper reaches of Spinaway Creek (Fig. 2B). In all those areas an unconformity was observed that corresponds to the unconformity mapped by Thom *et al.* (in Hickman, 1978). It is of low angle, on chert or chertified rocks. Basal pebbles, including chert and basalt, occur; the sections along the branches of Sandy Creek are the best exposed.

It is believed that this unconformity does not equate to the younger described (Lalla Rookh Sandstone), above the Soansville Subgroup, but to that basal to the Subgroup (Corboy Formation). The underlying rocks, re-examined in detail as far west as the Northern Highway, are dominantly pillow lavas, alternating with minor bands of chert, vesicular lavas and tuffaceous sediment. All pillows observed indicated younging to the east. The unit, marked (1) on Figure 2A, is believed to have been wrongly chosen by Hickman (1983) as the Corboy Formation equivalent. It is essentially of bleached pillow lavas, with some chert and chertified tuffaceous sediments at the top, similar to, and with no justification to be excluded from, the underlying Warrawoona Group volcanics, confirming subdivisions and mapping by Barley (1980, 1981). Hickman (op.cit.) and Lipple (1975) accordingly named the overlying unit "Charteris Basalt", (Table 1), and it is unfortunate that this area (marked (2) on Fig. 2A), was chosen as the type section for this formation, because basalts do exist in the Soansville Subgroup below the Paddy Market Formation in other areas about 100 km to the west.

The overlying sediments, above the basal conglomerate, in traverses a & b (Fig. 2B) are turbidites and grade from psephytes to pellites. They contain rare acid volcanics. Discordant chert veins occur (as indicated by Thom *et al.*, and recorded by Hickman 1983, p. 82) as well as large and small olistoliths of chertified sediment. As indicated on the geological sheet the unit grades up (but

with considerable interbedding) into cherts, chertified sediments and BIFs, in relationships, compatible with typical section of the Archaean illustrated by Anhaeusser (1971), and with genetic models described by Eriksson (1983) for BIFs in the Archaean of Southern Africa and Northern Western Australia. In agreement with Thom *et al.* most units were found to be chertified in section c (Fig. 2B).

Wherever observed, the younging persisted to be eastwards, right up to the boundary fault against the Warrawoona Group, thus avoiding the introduction of recumbant overfolds made by Hickman (1973, Fig. 3).

Traverses were later run across the unconformity of the southern part of the Kelly Belt, where a medium grained granitic rock intrudes the sequence in several sills. Our observations indicate that the sedimentary sequence is the same as the one in the north. Indeed, although interrupted, the sequences are of similar rocks and in strike extension along the whole belt, both contain rare acid volcanic rocks, and both show the same relationships to BIFs to the east.

Barley (1981, p. 265) records local unconformities, lower in the sequence, between rhyolite lava flows and basalts. Hickman & Lipple (1976) and Hickman (1983, p. 105) record an unconformity within the Warrawoona Group, at the base of their Duffer Formation. These unconformities in the volcanic piles are not relevant to this discussion.

No younger Archaean sequence, other than the basal unit of the Mt Bruce Supergroup, was recognized anywhere within the Kelly Belt. Some unconformable outliers of conglomerates and breccias, adjacent to fault line scarps, do occur, but they are considered to be associated with the development of the much later Hamersley Landscapes of Twidale *et al.* (1985).

Relationships to the Mosquito Creek area

Relationships of the Soansville Subgroup to the units of the Mosquito Creek area are not yet fully confirmed by field traverses. However, observations in the Brunette Hill general area, to the south of Mosquito Creek, clearly indicate that BIFs are part of the turbidite sequence of the Mosquito Creek Formation of Thom *et al.* (in Hickman 1978). Their mapping around the McPhee Dome indicates that nowhere does the Formation rest upon units comparable to the Paddy Market Formation. The dominance of turbidites in both, the Mosquito Creek Formation and the Soansville Subgroup of the Kelly Belt, argues in favour of their correlation, rather than equating one or the other to the Younger sequences, in which similar facies only occur in the Mallina Trough area some 200 km to the northwest.

The Mosquito Creek Formation, or part of it at least, is thus tentatively assigned to the Soansville Subgroup and unless it is a very complex sequence composed of two unconformable formations, it would appear that the Whim Creek Group, and other young Archaean sequences such as the Lalla Rookh Sandstone, are not preserved, or did not extend, as far east and south as the Kelly Belt.

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Addendum

Two Tables referred to the paper by De Laeter & Baxter were inadvertently omitted from the paper (**J R Soc W Aust** 69: 113-116).

Table 1.

Rb/Sr data for the Mulgine Granite

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
216	-	-	0.878 ± 0.009	2.54 ± 0.03	0.79823 ± 0.0005
215	-	-	0.99 ± 0.01	2.89 ± 0.03	0.81304 ± 0.0005
175	-	-	1.48 ± 0.02	4.34 ± 0.04	0.87017 ± 0.0006
173	-	-	1.70 ± 0.02	5.05 ± 0.05	0.90001 ± 0.0007
228	-	-	2.00 ± 0.02	5.91 ± 0.06	0.92796 ± 0.0006
214	-	-	2.25 ± 0.03	6.69 ± 0.07	0.95964 ± 0.0007
219	-	-	2.43 ± 0.03	7.22 ± 0.07	0.98121 ± 0.0008
*E295	456	187	2.44 ± 0.03	7.24 ± 0.07	0.98993 ± 0.00071
*E421	313	96	3.29 ± 0.03	9.82 ± 0.09	1.06126 ± 0.00031
*A	344	74	4.64 ± 0.05	14.1 ± 0.1	1.22000 ± 0.00023
*E294	514	54	9.48 ± 0.09	30.6 ± 0.3	1.91480 ± 0.00090
*296	410	20	20.0 ± 0.2	73.4 ± 0.7	3.47467 ± 0.00080
255	-	-	26.1 ± 0.3	100 ± 1	4.1102 ± 0.0035
247	-	-	49.5 ± 0.6	264 ± 3	9.3947 ± 0.0071

*Drill-core samples

Table 2.

Rb/Sr data for the porphyritic biotite granitoid from Mount Mulgine

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
272	-	-	1.80 ± 0.02	5.27 ± 0.07	0.90180 ± 0.0004
264	-	-	2.63 ± 0.03	7.78 ± 0.09	0.99558 ± 0.0005
268	-	-	2.68 ± 0.03	7.96 ± 0.09	1.00562 ± 0.0004
273	-	-	3.12 ± 0.03	9.31 ± 0.10	1.04884 ± 0.0003
265	-	-	3.24 ± 0.03	9.68 ± 0.11	1.06809 ± 0.0005
270	-	-	3.43 ± 0.03	10.25 ± 0.12	1.06323 ± 0.0005
275	-	-	3.53 ± 0.04	10.58 ± 0.13	1.10013 ± 0.0004
266	-	-	3.58 ± 0.04	10.71 ± 0.13	1.08032 ± 0.0005
*5001	325	87	3.71 ± 0.04	11.1 ± 0.1	1.12534 ± 0.00026
267	-	-	4.09 ± 0.05	12.28 ± 0.15	1.11395 ± 0.0005
*5005	319	73	4.34 ± 0.04	13.1 ± 0.1	1.19641 ± 0.00046
*E291	364	65	5.56 ± 0.06	17.1 ± 0.2	1.34592 ± 0.00081
271	-	-	7.88 ± 0.09	24.5 ± 0.3	1.54009 ± 0.0006

*Drill-core samples

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The *Journal* publishes (after refereeing)

- papers dealing with original research done in Western Australia into any branch of the natural sciences;
- papers concerning some biological or geological aspect of Western Australia;
- authoritative overviews of any subject in the natural sciences, integrating research already largely published in the more specialized national or international journals, and interpreting such studies with the general membership of the Society in mind;
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Book Jacobs M R 1955 Growth Habits of the Eucalypts. For Timb Bur, Canberra.

Chapter in book Dell J 1983. The Importance of the Darling Scarp to Fauna. In: Scarp Symposium (ed J D Majer) W Aust Inst Technol, Bentley, 17-27.

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